VOLUME XVII JANUARY, 1952 NUMBER 1

GEOPHYSICS

A Journal of General and Applied Geophysics

MAGNETIC WELL LOGGING*

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ABSTRACT

The need for control data in interpretation of surface magnetometer surveys has led to the development of borehole instruments for measuring magnetic susceptibility and total magnetic field in situ. The susceptibility instrument is an alternating current induction device, and by separation of the quadrature components simultaneous recording of the magnetic susceptibility and the electrical conductivity is possible. The susceptibility log has many features that depart from ordinary electric logs. The instrument has a sensitivity of the order of 1×10^{-6} cgs units and sufficient contrast has been found in the sediments to yield a log of considerable lithologic character. This magnetic character suggests the use of the susceptibility tool in the field of special well logging, particularly for geologic correlation, and for tracer studies. The general assumption that the magnetic susceptibility of the sediments is sufficiently low compared to basic igneous rocks so that sedimentary rocks have little effect on surface magnetometer measurements has been verified. Since the magnetic susceptibility and electrical conductivity logs are made with an induction instrument, an electrolyte is not required in the hole and the logs are independent of the drilling fluid, except that the conductivity log is influenced by highly conductive muds.

The total field log is made with a three element self-orientating saturable core magnetometer that has been developed for borehole use. This log has not been used extensively. In addition to reflecting changes in polarization of the formations, it is influenced by formation susceptibility. Logs have been made of the total field going into and through igneous plugs.

The paper presents examples of these logs along with a brief description of the instruments developed to produce them.

INTRODUCTION

In the interpretation of surface magnetometer surveys it is necessary to make certain assumptions regarding the magnetic material in the earth and its environment before it is possible to find a unique solution to the problem of determining the geological features represented by the magnetic anomalies. In order to test the validity of the assumptions made in specific cases, and to collect data hitherto unavailable, the Field Research Laboratories of Magnolia Petroleum Company have developed two magnetic well logging instruments. These new instruments log magnetic susceptibility and total magnetic field.

The magnetic susceptibility tool has been under development and in restricted

* Presented at the St. Louis Meeting of the Society April 25, 1951. Manuscript received by the editor August 16, 1951.

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use for the past three years. It is considered to be quite well developed at this time and has many features that make it attractive to the petroleum industry.

While the possibilities of the total field instrument, developed concurrently with the susceptibility tool, have not been thoroughly explored, a measurement of the magnitude of the total field either at points in a borehole or continuously along the length of a borehole may be used to advantage for study or location of formations with high remanent magnetism.

This paper describes the instrumentation of these tools and summarizes the preliminary field work that has been done.

INSTRUMENTATION

The Induction Tool

In its present form the sensitive element of the induction logging tool is a long solenoid wound around a conpernik core. At a given excitation frequency the coil has a certain impedance Z; see Figure 1. Contrasts in formation susceptibility produce contrasts in the reluctance of the external magnetic path of the solenoid and thus change the inductance of the coil by a small amount proportional to the magnetic susceptibility of the surrounding formation. This induct-

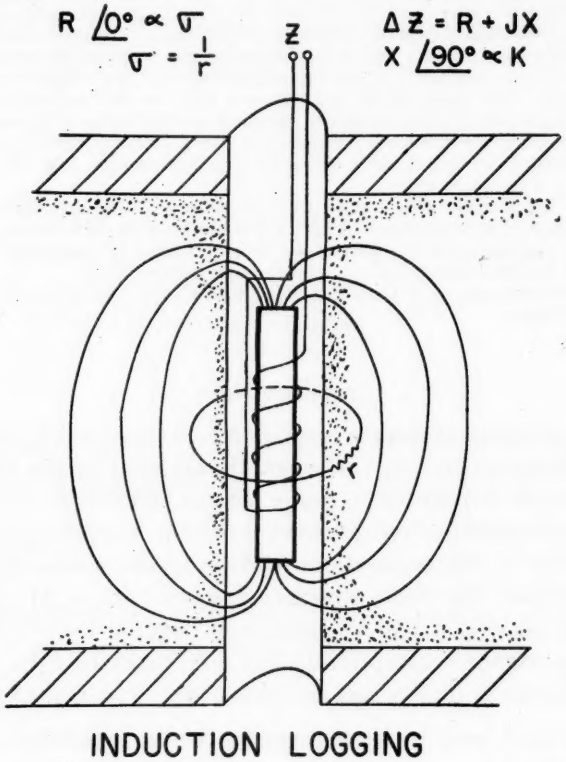

FIG. 1. Schematic representation of the energized solenoid in a well bore.

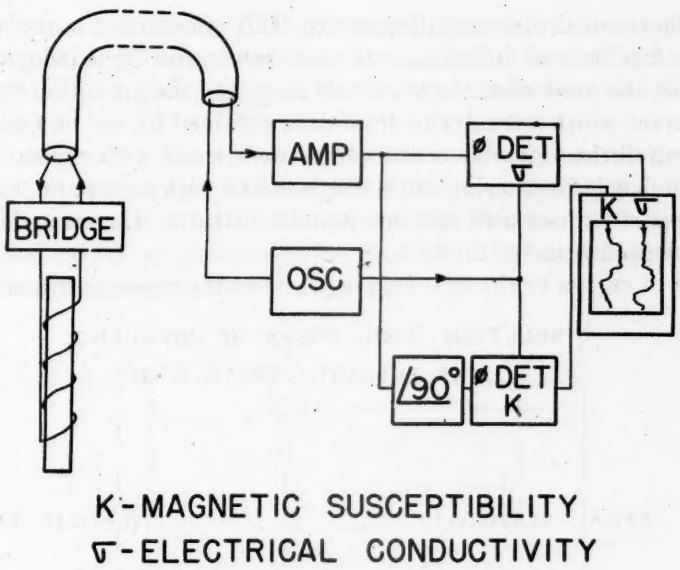

FIG. 2. Block diagram of the induction logging system.

ance change is purely a reactive component and gives rise to a change in only the quadrature component jX of the impedance Z. In addition to the above mentioned magnetic susceptibility sensitivity, the coil, because of induction coupling to the surrounding rock, will induce currents in the formation. These currents are proportional to the formation conductivity, σ or $1/r$, and through mutual coupling reflect back into the coil a resistive component, R. It is well to note that these induced currents flow around a horizontal path in contrast to the vertical path used in conventional resistivity logging. This feature allows the induction conductivity component to give a more accurate measurement in thin horizontally stratified beds. In the practical instrument the solenoid is connected as one arm of a bridge. If the bridge is balanced in air and then inserted into the borehole, the bridge becomes unbalanced by the amount ΔZ. The total bridge unbalance signal is separated into its resistive and reactive components by phase sensitive detectors so that the electrical conductivity and magnetic susceptibility are recorded independently and simultaneously.

Figure 2 is a simplified block diagram of the induction logging system. The coil and bridge make up the investigating device and are shown attached to the logging cable. The oscillator is at the surface and is shown feeding the excitation current into the investigating device and a reference signal into the phase detecting networks. The amplified bridge unbalance is split into two channels with the signal in one channel being shifted 90° with respect to the other. These signals are applied to separate phase detectors and recorded as magnetic susceptibility and conductivity.

In the development of a new logging system it is necessary to determine the

field of influence of the investigating device. This information is needed in interpreting the logs because it indicates to what extent the log is influenced by the drilling mud, the mud cake, the transition zone, and the formation itself. Figure 3 shows curves which were drawn from data obtained by use of a model of the investigating device. Simulated formations were made with cement disks containing iron powder in varying concentrations and with concentric wooden rings used to support various sand and iron powder mixtures. These simulated formations were logged with the model tool.

The set of curves to the left, Figure 3, shows the response in percent of the

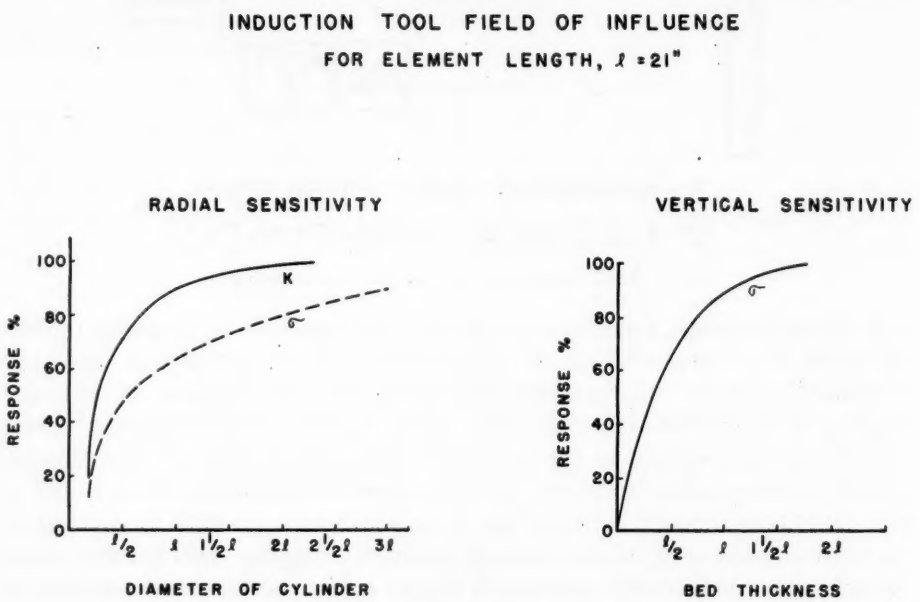

FIG. 3. Curves showing the field of influence of the induction tool.

two components as a function of the diameter of the borehole in a cylindrical bed of infinite thickness. This diameter is measured in terms of the length l, of the sensitive coil and core. It may be determined from this set of curves that the response is not the same for each component, and that the susceptibility component is influenced largely by the material adjacent to the tool out to a diameter of one coil length, while the conductivity component is influenced by the material adjacent to the tool extending to a diameter of three coil lengths. The point of 90 percent response was used in each case to determine these diameters.

The curve at the right shows the response of the conductivity component as a function of the thickness of the bed. Again, the bed thickness is expressed in terms of the length, l, of the sensitive element. From these curves it can be seen that the values read directly from the log will be apparent susceptibility or conductivity which will be different, in many cases, from true susceptibility or con-

ductivity of the formations. These curves will permit a closer approach to true values by providing correction factors for variations in bed thickness and also for susceptibility or conductivity of the drilling fluid in the borehole at the time the logs are run.

These curves also illustrate the point that the design of the coil requires a compromise between a long coil for penetration into the formation and a short coil for delineating thin beds with good detail. We are presently using a coil that gives a radius of penetration of 12 and 36 inches, respectively, for the susceptibility and conductivity components.

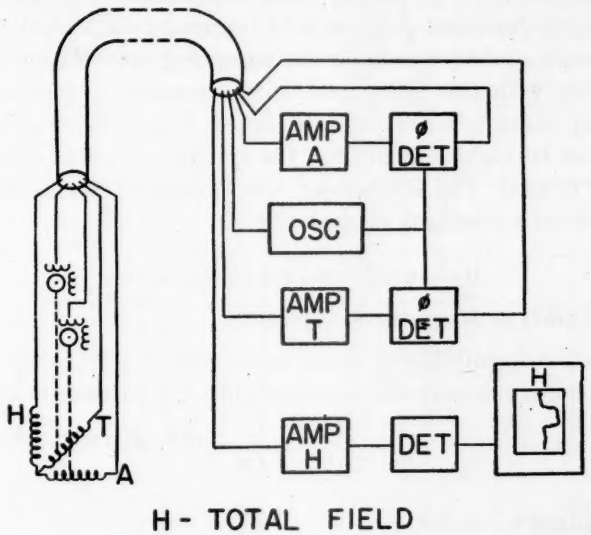

FIG. 4. Block diagram of the total magnetic field logging system.

Total Magnetic Field Tool

This instrument is a modification of the magnetic airborne detector equipment developed during the past war which has since been widely used in airborne magnetometers for geophysical surveys.[1]

The sensitive element is a saturable core magnetometer. This magnetometer element must be aligned with the earth's field to measure total field.

The alignment is automatically accomplished by two sensitive elements similar to the measuring element mounted at right angles to one another in a given plane. The measuring element is perpendicular to the plane of the aligning coils. With this arrangement, when the plane of the aligning coils is parallel to the magnetic horizon the aligning coils are in zero ambient field and the measuring element is correctly aligned to produce maximum response from the earth's field. During the logging run the instrument case may rotate and the aligning coils will no longer be in zero ambient field. An error signal will be produced

[1] R. D. Wycoff, "The Gulf Airborne Magnetometer," *Geophysics*, XIII, (April 1948), 182–208.

in either one or both of these coils and, after proper amplification, is used to actuate one or both servo motors. These motors are coupled to a gimbal supported platform on which the sensitive elements are mounted. Thus, a misalignment is immediately corrected by the servo system which returns the aligning coils to zero ambient field and the measuring coil to maximum ambient field.

A simplified block diagram of the system is shown in Figure 4. The axial and transverse aligning coils are marked *A* and *T*. The measuring coil is *H*. The servo motors are shown coupled to *A* and *T*. This comprises the essential portion of the investigating device which is lowered into the well on the logging cable. The surface equipment is, of course, more complicated than is shown by the diagram, but its fundamental purpose is to terminate the two aligning elements in the servo system and to terminate the measuring element in the recorder.

Before logging with this equipment it is necessary to bias out the earth's field so that only changes in the field are logged. This permits a high sensitivity to be used, and at its highest sensitivity the system is capable of detecting a one gamma change in field. The instrument was calibrated by use of a Helmholtz coil which produced a standard magnetic field.

MAGNETIC SUSCEPTIBILITY LOGS

Representative Values of Magnetic Susceptibility

The magnetic susceptibility of rocks varies over a wide range. Figure 5 is a brief table of some of our magnetic susceptibility measurements made of natural

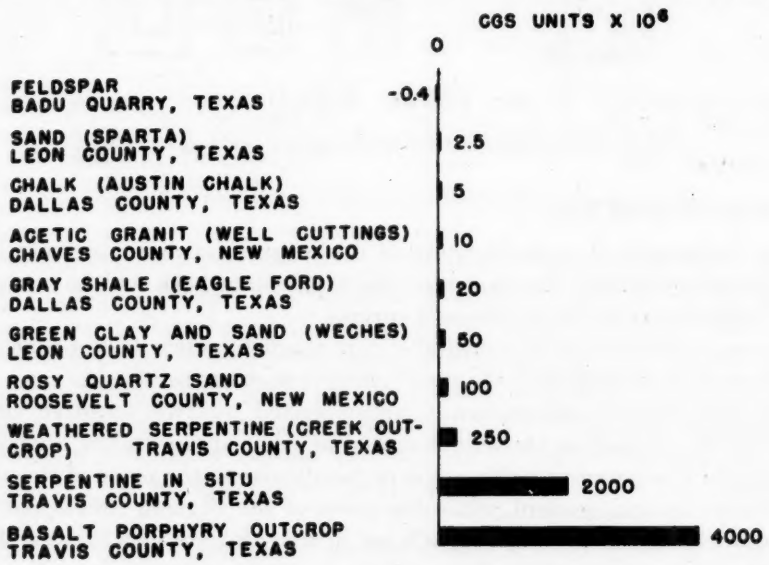

FIG. 5. Bar diagram showing the range of susceptibility values for selected formations.

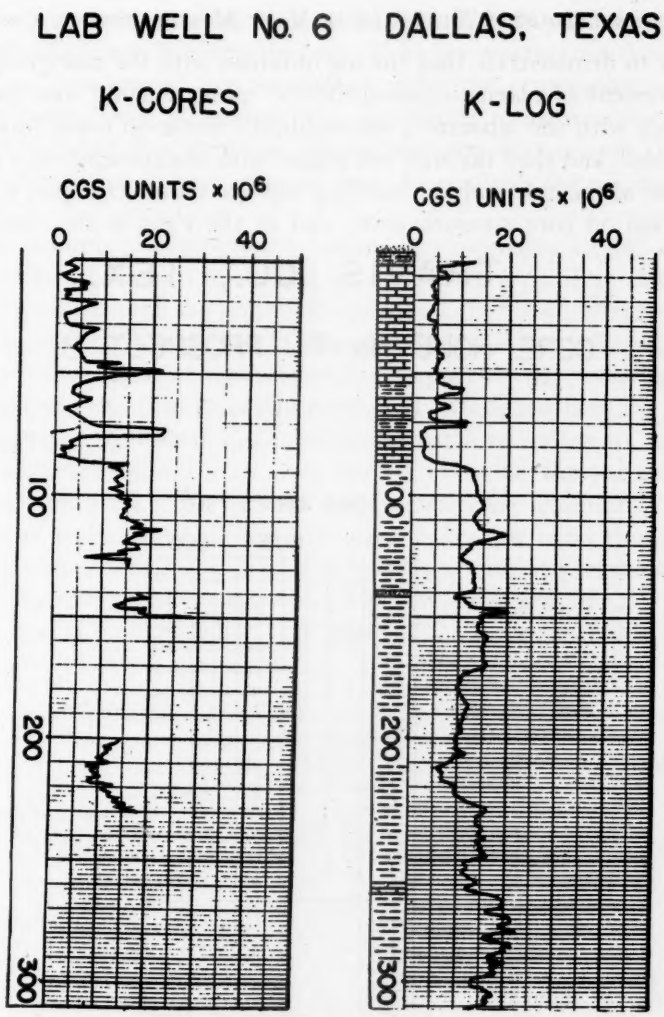

FIG. 6. Comparison between a susceptibility log based on laboratory measurements of cores and the continuous log.

rock. The feldspar found in the Badu Quarry was a creamy orthoclase and was diamagnetic. Salt and coal are also diamagnetic substances. Most sandstones contain either hematite, limonite, or magnetite and have widely varying susceptibilities. Chalk and limestone are usually weakly paramagnetic. Igneous rocks have an extremely wide range of magnetic susceptibilities, from acidic granites which are very low to the basalts and other basic rocks which may exceed the 4000×10^{-6} cgs units recorded here. Magnetic susceptibility logs are analogous to gamma ray logs in that each measures a natural property of the rock which is not necessarily specific to rock type. For example, some shales are radioactive, others are not. Some shales are paramagnetic, others only weakly so.

Correlation with Laboratory Susceptibility Meter Measurements of Cores

In order to demonstrate that the log obtained with the susceptibility device is a measurement of magnetic susceptibility, measurements were made at one foot intervals with the laboratory susceptibility meter on cores from a shallow laboratory well, and then the well was logged with the susceptibility device. The cored section of the hole and the resulting logs are shown in Figure 6. At the left is a log based on core measurements, and at the right is the continuous log.

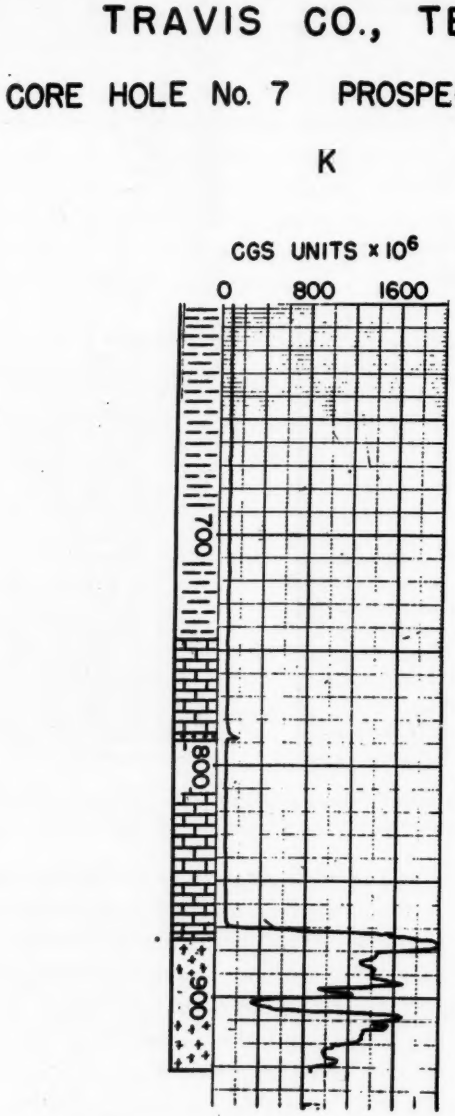

FIG. 7. A susceptibility log into an igneous mass of high susceptibility.

Although the correlation is good, it is not perfect. This may be explained by the fundamental differences between the logs. The core measurements are made on very small sections spaced one foot apart while the continuous log averages values over several feet of section; the core depth measurements may be in error, especially when less than 100 percent recovery is obtained; the densities of the cores may be slightly in error so that the resulting volume susceptibility is inaccurate.

A second example of correlation between the continuous log and a log based on laboratory measurements of cores is shown in Figure 15. Here the sensitivity is greatly reduced so that the sediments above 660 feet are not shown in detail but instead appear to be very low in magnetic susceptibility. The section below 660 feet is an igneous mass of high magnetic susceptibility which had been located by a magnetic vertical field intensity survey. It is believed that the sensitivity used here actually represents the relationship between sediments and igneous material of high susceptibility in their mutual effect on the earth's magnetic field at the surface. That is, the effect of most sedimentary material on the earth's field is believed to be slight. Unless this point is kept in mind the great detail found on the higher sensitivity logs may overemphasize the importance of the sedimentary material on a magnetic survey. A second example of a low sensitivity log into an igneous mass is shown in Figure 7. The position of this well in the magnetic anomaly is shown in Figure 16.

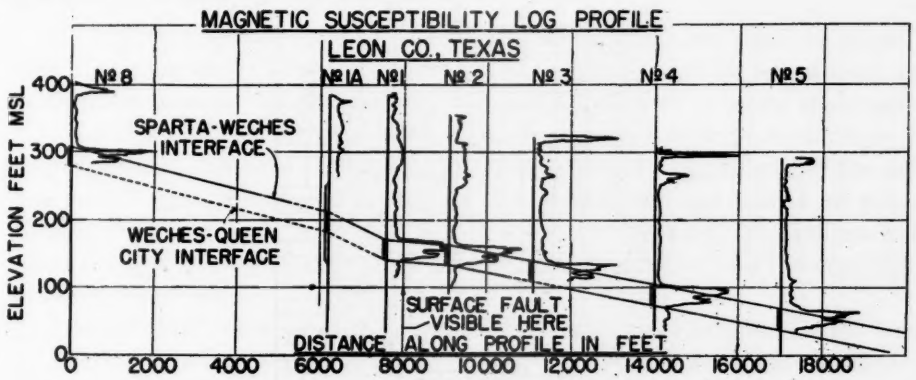

FIG. 8. A profile based on susceptibility logs showing how the Weches stands out from the Sparta and Queen City formations.

Magnetic Susceptibility Logs in Correlation Work

The magnetic susceptibility log has been used in correlation studies and may be used to advantage where strong magnetic marker beds are found. Figure 8 is a profile based on susceptibility logs made of core holes on a prospect in Leon County, Texas. This profile demonstrates the fact that a given stratum of relatively high magnetic susceptibility—in this case the Weches green clay and sand formation—may be followed over a considerable distance and that both

interfaces of such a stratum will be sharply defined. In holes No. 8, No. 1A, and No. 3 the loose Sparta sand above caved in and prevented the investigating device from penetrating the Weches stratum. The magnetic marker material in the Weches is glauconite. In this case pure glauconite has a susceptibility near 200×10^{-6} cgs units. With an instrument resolution of 1×10^{-6} units we should be able to detect glauconite to one part in 200. The Weches sand having a susceptibility of 50 cgs units should contain approximately $\frac{1}{4}$ glauconite.

Correlation Between Permeability of a Stratum and Magnetic Susceptibility

Routine comparisons of magnetic susceptibility logs with radioactivity logs, electrical logs, and core analysis data have disclosed many interesting correlations. One such correlation that appears often is illustrated in Figure 9. These

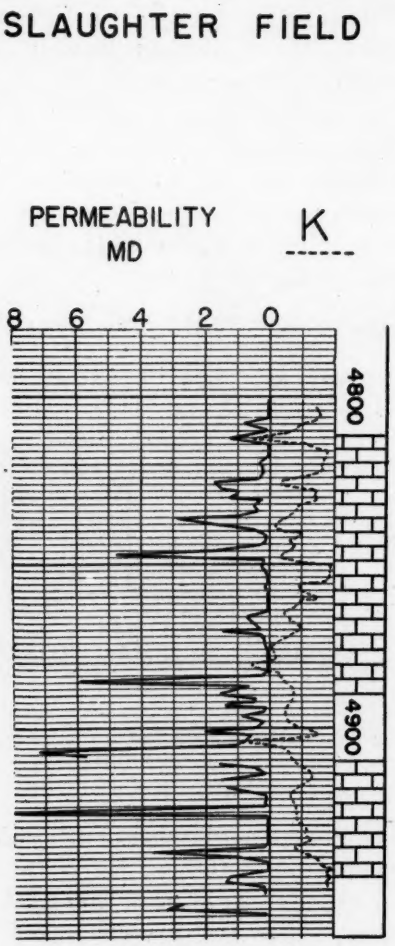

FIG. 9. Correlation between the permeability and magnetic susceptibility of a limestone reservoir.

logs are of the pay section of a limestone producer in the Slaughter Field, Hockley County, Texas. The permeability measurements are laboratory core data on 18 inch cores. The dotted curve is a continuous susceptibility log of the cored section, with increasing response to the left. The correlation between the two is good in the upper half, rather poor in the lower half. In this and following examples where magnetic susceptibility increases in the permeable zones the suggested explanation is that ground water, percolating through the permeable rock, deposited iron compounds to which the log is sensitive. As more logs are obtained the validity of this correlation between permeability and susceptibility will be tested. The idea is again illustrated in this report in Figures 11 and 13 where susceptibility response often correlates with negative breaks in the self potential logs. This apparent phenomenon of natural magnetic tracers being concentrated in permeable zones has suggested the use of artificial tracers, such as finely powdered iron, in drilling muds to mark permeable zones. Preliminary tests of the use of iron powder as a magnetic tracer in drilling muds have been made. These tests indicate that a significant concentration of iron can be built up in the mud cake to clearly delineate the zones where mud cake has formed. Apparently, a small amount of iron powder invasion into the formation also takes place in porous and permeable zones. Further tests to evaluate this method of delineating the permeable zones in a borehole are being planned.

Simultaneous Susceptibility and Conductivity Logs

An experiment was made to determine whether good logs could be made in hole above the water level and is illustrated in Figure 10. This experiment was undertaken because the conventional shot hole logger used to locate shale strata for seismic shooting failed when drilling fluid could not be kept in the hole. In this experiment the hole was logged immediately after being drilled and the solid line curves were recorded. The drilling fluid was blown out with a 20 pound charge of powder and the dotted line curves were recorded. The curves were offset to avoid overlapping. In these records both conductivity and susceptibility increase to the left.

Logs of three wells in widely separated oil fields were selected on the basis of differing lithology and drilling mud resistivities. These fields are the Sholem Alechem Field, Carter County, Oklahoma; the Slaughter Field, Hockley County, Texas; and the Kelly-Snyder Field, Scurry County, Texas. The induction logs, magnetic susceptibility K and electrical conductivity σ, are recorded with increasing response to the left. The S.P. and resistivity curves were made by a commercial logging company, the resistivity curve being the short normal. No mathematical relationship exists between S.P. and susceptibility, but conductivity and resistivity are reciprocals.

The mud resistivity in Figure 11 was 2.3 ohm meters at 79°F. This resistivity is high enough to permit all four curves to respond in a normal manner. The correlation between conductivity and resistivity is good if allowance be made for

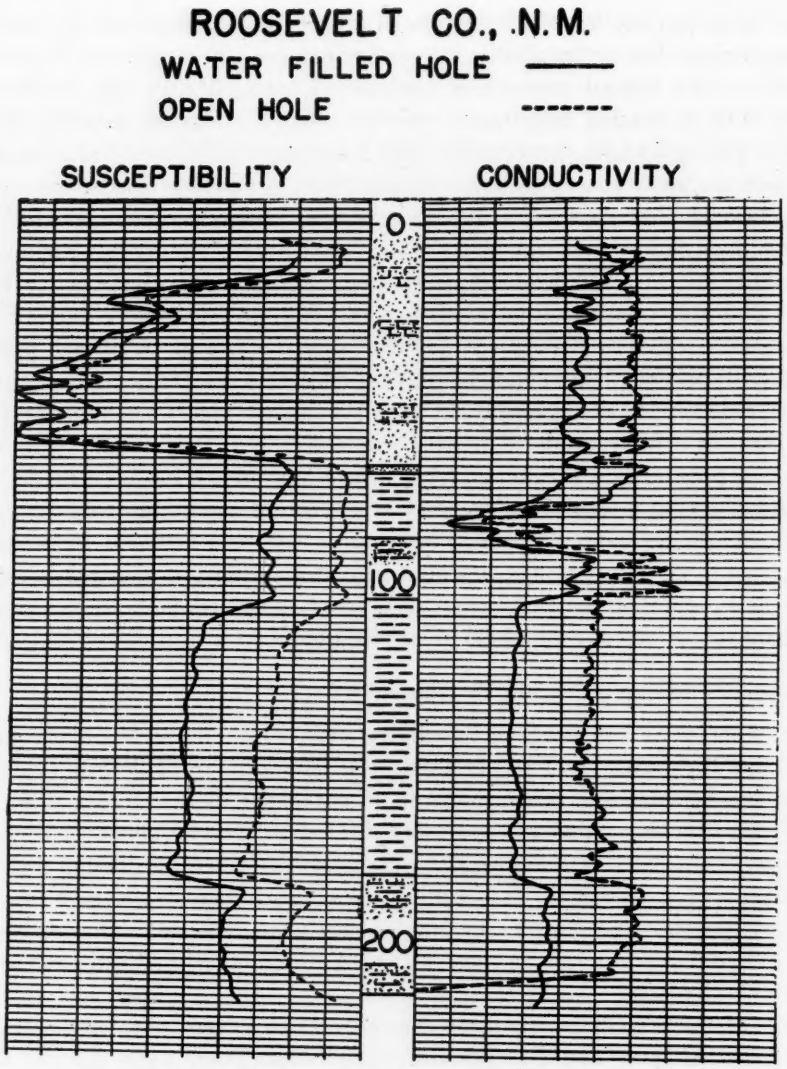

FIG. 10. Comparison between logs made with and without water in the hole.

the reciprocal relationship between the curves. The magnetic susceptibility scale is 100×10^{-6} cgs units full scale. There is a considerable amount of character in the magnetic susceptibility log and in several cases there is good correlation with the self potential log. Correlations of this type support the possibility of iron concentrations in permeable zones.

In the Slaughter Field, Figure 12, the mud resistivity was low, only 0.05 ohm meters at 75°F. Here the conventional self potential curve and some resistivity logs fail. The conductivity log is also unreliable and is probably of

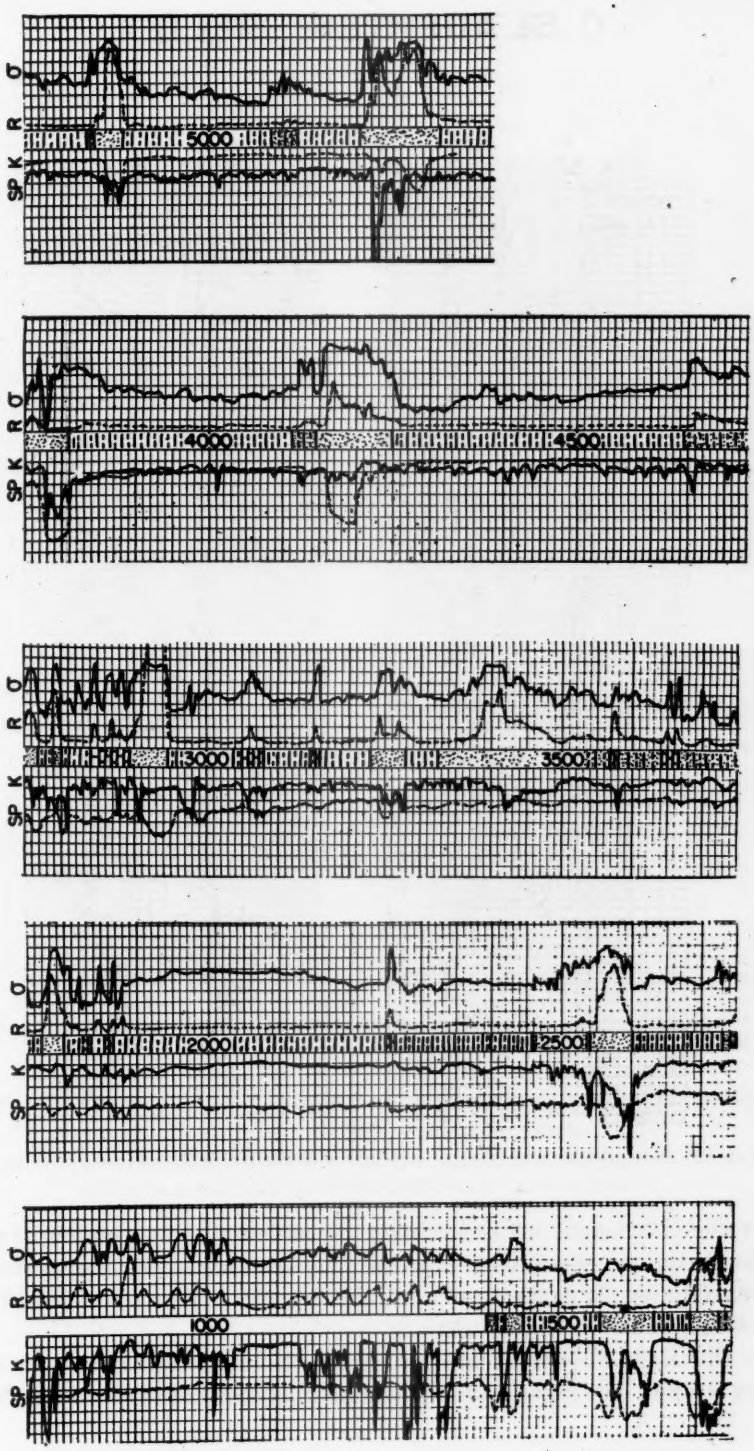

FIG. 11. Susceptibility and conductivity logs compared with SP and resistivity logs of a well in Oklahoma (Mud resistivity 2.3 Ohm-m at 79°F.).

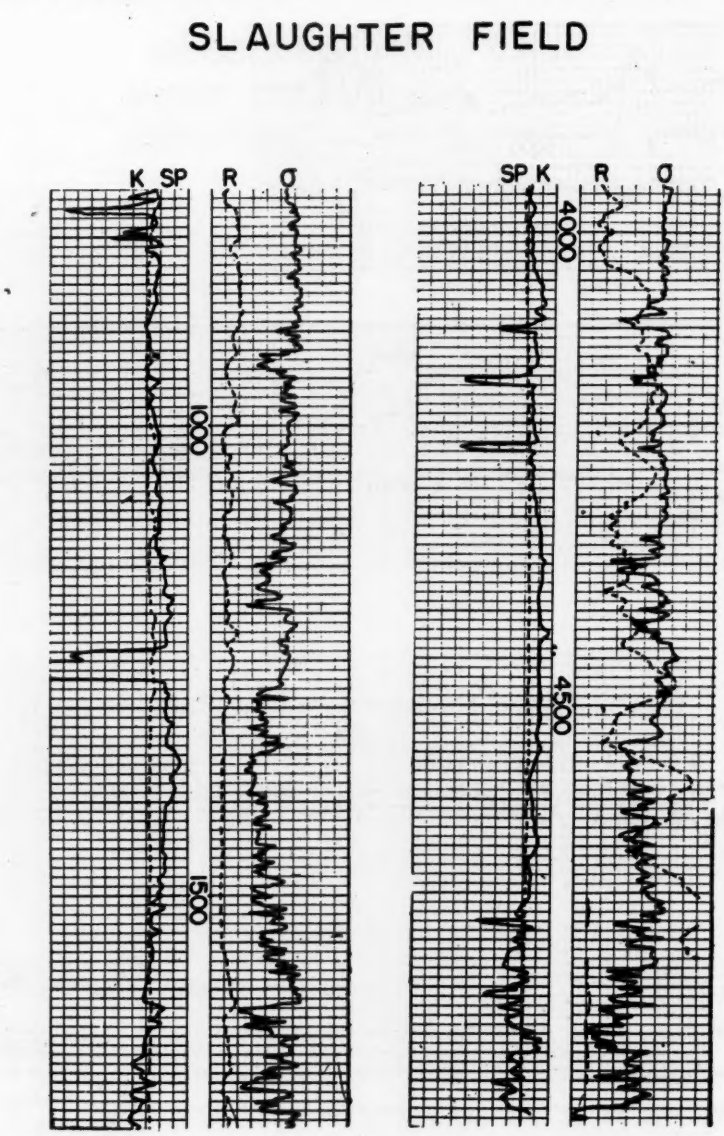

FIG. 12. Susceptibility and conductivity logs compared with SP and resistivity logs of a well in West Texas (Mud resistivity 0.05 Ohm-m at 75°F.).

little value. The magnetic susceptibility log, however, is independent of resistivity (or conductivity) since this component has been separated and made into the conductivity log. It is therefore a reliable log and is representative of the magnetic susceptibility of the formations.

In the Kelly-Snyder Field, Figure 13, the mud resistivity was 0.88 ohm meters at 87°F. The resistivity and conductivity logs are again adversely affected

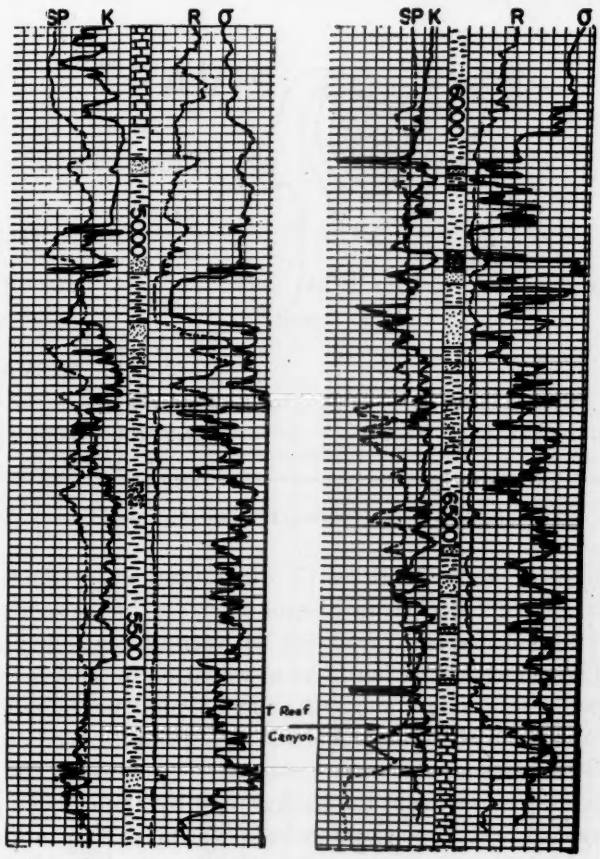

FIG. 13. Susceptibility and conductivity logs compared with SP and resistivity logs of a second well in West Texas (Mud resistivity 0.88 Ohm-m at 87°F.).

by the low resistivity mud, but appear to have some value. The magnetic log and S.P. have some points of agreement at permeable zones.

TOTAL FIELD LOGS

Figure 14 shows the vertical field intensity contours of a magnetic anomaly located in Travis County, Texas. A core hole was drilled into the center of the well defined high and logged. At a depth of 665 feet a formation of igneous origin was encountered. Figure 15 shows three logs, the first based on laboratory measurements of the susceptibility of cuttings and cores, the second the continuous susceptibility log, and the third the total field log. The total field log

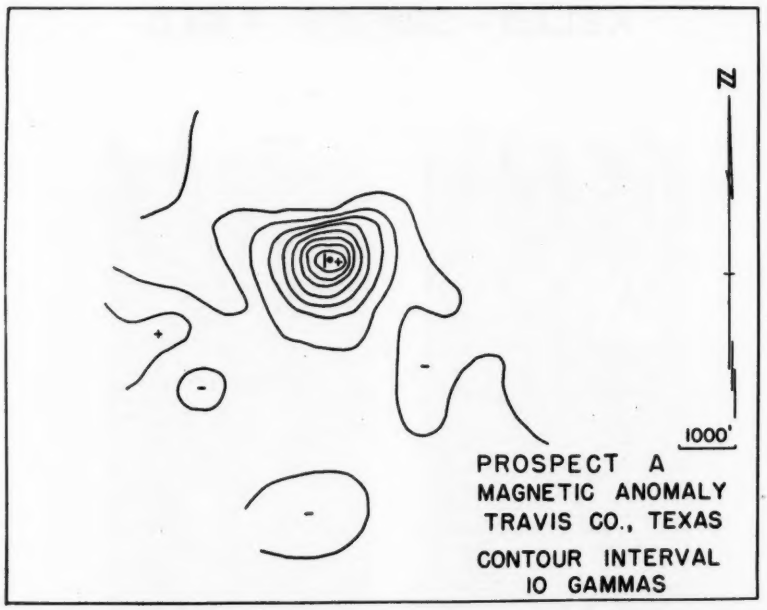

FIG. 14. Vertical field intensity contours, Prospect A, Travis County, Texas.

increases non-linearly with depth until the investigating device enters the igneous material. Here there is an abrupt decrease in magnetic field. There appears to be a sort of inverse correlation between susceptibility and magnetic field within the igneous body. A tentative explanation for this is that the highly susceptible material serves as a magnetic shield similar to the mu-metal shields used in laboratories, and that the higher the susceptibility the better the shield. The susceptibility values go well over $3{,}200 \times 10^{-6}$ cgs units in the igneous mass and the total field increases from the background by about 8,000 gammas with an abrupt decrease of near 7,000 gammas inside the mass. It is interesting to note that only about $\frac{1}{3}$ of this abrupt decrease in field can be accounted for from the induced field. Therefore, it follows that remanent magnetism must be influencing in the field to a large extent. The core susceptibility log and the log taken in situ compare very well in character and absolute values.

Figure 16 shows another magnetic anomaly in the same general area. This anomaly is shaped differently, having considerable extent in the east-west direction. The anomaly is well defined, being some 240 gammas above the background. Core hole No. 10 was drilled through the igneous material which at that point was 150 feet thick. The logs made of this hole are shown in Figure 17. Both logs are recorded at two sensitivities, the units for which are recorded at the top of the figure. Again the total field log decreases abruptly as it enters the igneous plug and in an imperfect way follows the rule that where susceptibility is high, magnetic field is low. There is a radical difference, however, in the

total field logs of this prospect compared to Figure 15. This log shows no increase in field as the instrument approaches the igneous mass, yet the positive anomaly is stronger here than in Figure 14. Other logs of the prospect, Figure 16, not shown in this report, are similar in that no increase is shown as the investigating device approaches the igneous mass.

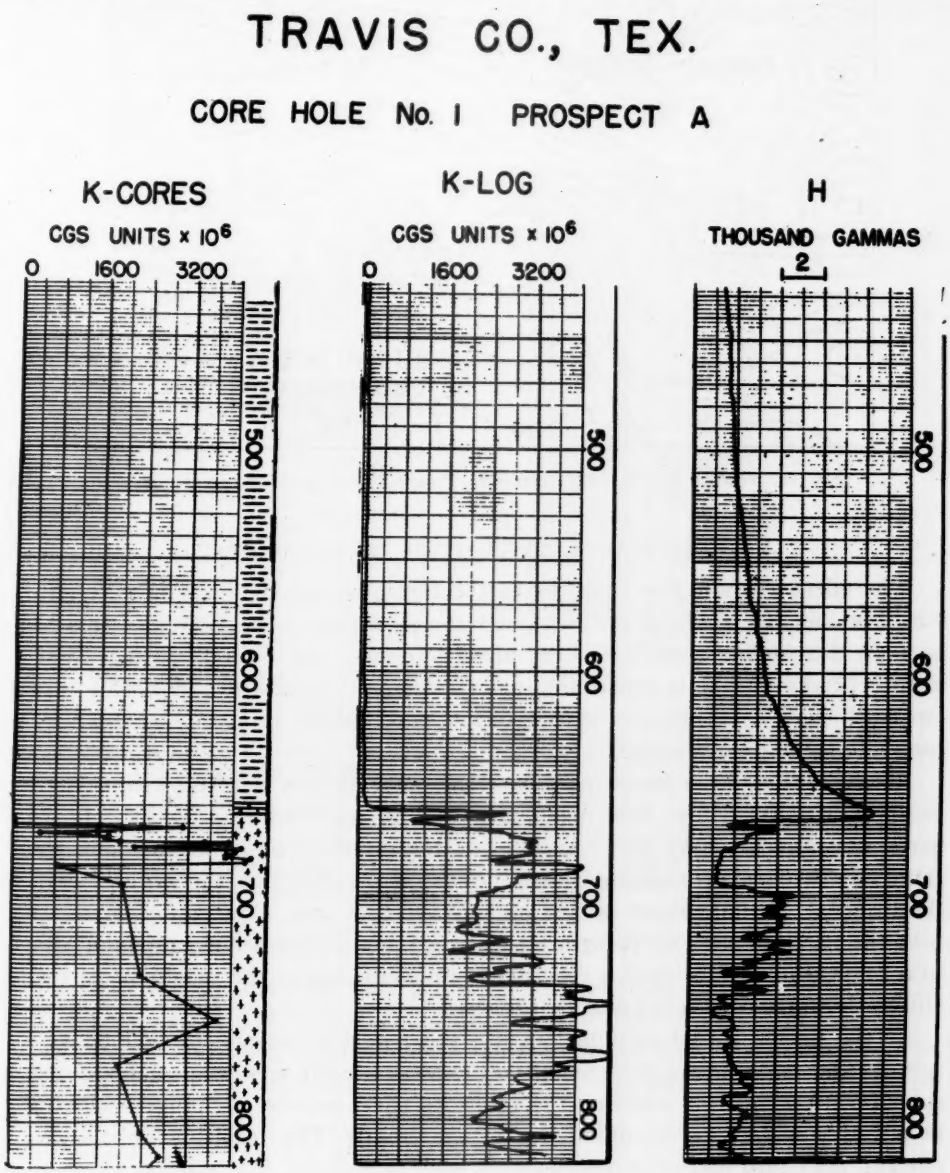

FIG. 15. Susceptibility and total field logs of Core Hole 1, Prospect A.

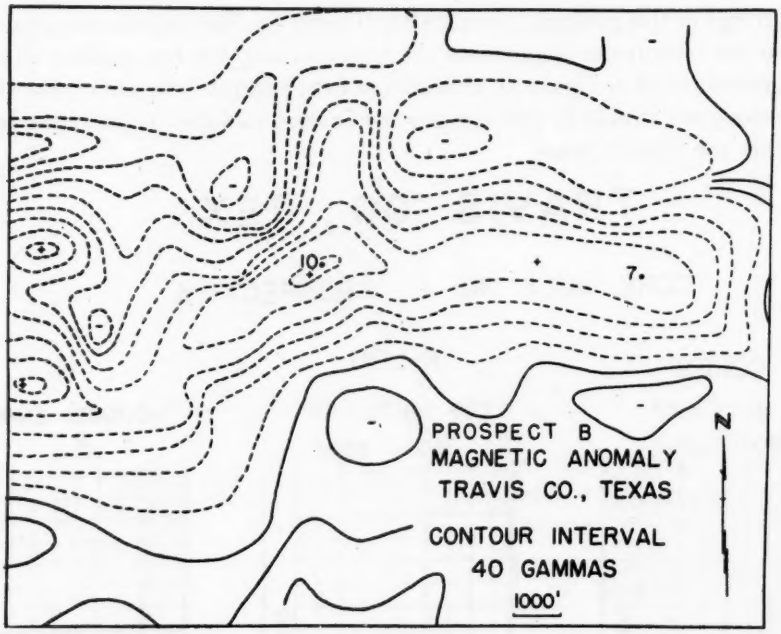

FIG. 16. Vertical field intensity contours, Prospect B, Travis County, Texas.

MATHEMATICAL ANALYSIS OF THE INDUCTION TOOL

The effect of inductive coupling to the formation on the impedance of the sensitive coil was briefly described under the *Instrumentation* section of this report. In this section the effect is examined in detail, and a mathematical treatment is presented which, explaining the experimental properties exhibited by the tool, will permit calculation of the region of influence of each component—conductivity and susceptibility.

When excited at a fixed frequency the solenoid has a certain impedance value. For convenience, this impedance can be considered to consist of two parts: one, the constant part consisting of the internal self-impedance and the external self-impedance arising within the case of the tool; two, the variable part, the external self-impedance arising outside the tool case. Concerning ourselves with the variable part, we recognize two components, a resistive component due to a finite conductivity and a reactive component due to the magnetic permeability, both from material outside the case.

If the bridge circuit is nulled in air, the resistive component will be zero ($\sigma=0$), and the reactive component will possess a finite free-space value corresponding to $\mu=\mu_0$. By lowering the tool into the borehole, a change occurring in μ and σ will cause an unbalance in the bridge. The resulting unbalanced current, split into its two components, is used to measure the resistance and inductance changes of the solenoid impedance. The resistance change is directly

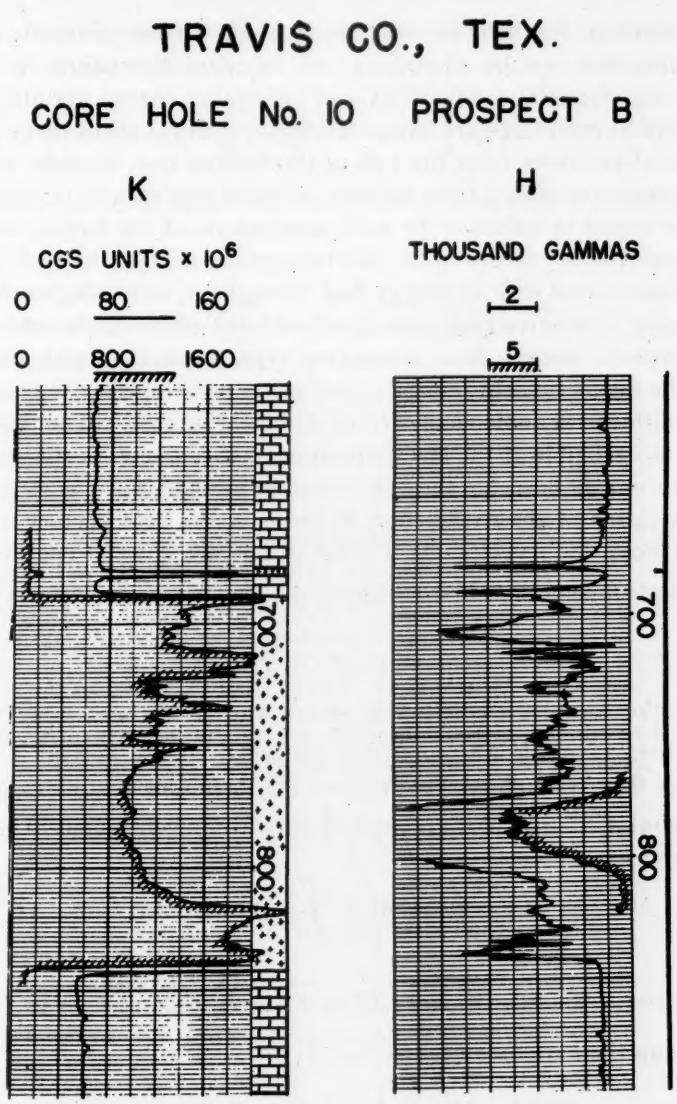

FIG. 17. Susceptibility and total field logs of Core Hole 10, Prospect B.

related to the conductivity change, $\Delta\sigma=\sigma-\sigma_0$, while the inductance change is directly related to the magnetic susceptibility change,[2] $\Delta\chi_m=\mu_0^{-1}(\mu-\mu_0)$.

The problem, then, is to calculate the changes in both components of the variable part of the self-impedance of the coil arising from different sections of

[2] The terminology used throughout this section of the report is that used in J. A. Stratton, *Electromagnetic Theory*, McGraw-Hill (1941). Here the magnetic susceptibility, $\Delta\chi_m$, is given in M.K.S. units; the value given previously, in terms of ΔK, is the magnetic susceptibility in cgs units. A factor of 4π exists between them; $\Delta\chi_m=4\pi\Delta K$.

the rock formation. So that the variation of μ and σ from section to section in the rock formation can be eliminated, we calculate the values of resistance change per unit electrical conductivity and inductance change per unit magnetic susceptibility. These values are computed for cylindrical shells of rock, located different radial distances from the axis of the logging tool, in order to estimate the relative response arising from different annular regions and to permit one to estimate the region of influence for both components of the logging tool.

The solenoid is the source of an electromagnetic field in the rock formation. This field is associated with an energy flow throughout, consisting of three types: Joulean energy, a resistive type, associated with the eddy current and dissipated as heat; magnetic energy flow, a reactive type, associated with the periodic change in the magnetic field intensity; and electric energy flow, a reactive type, associated with the periodic change in electric field intensity. The latter of type energy flow is negligible at the low frequency employed here, so that the Joulean and magnetic energy flows are the only two of importance.

The evaluation of the energy flow in terms of the field vectors is described in terms of Poynting's vector. At a point in space the mean energy flow of a harmonic electromagnetic field is represented by a complex Poynting vector ($\vec{S^*}$);

$$\vec{S^*} = 1/2(\vec{E} \times \vec{\bar{H}}), \tag{1}$$

where $\vec{E}$ is the complex electric field vector and $\vec{\bar{H}}$ is the complex conjugate magnetic field vector. If $\vec{S^*}$ represents the mean energy flow at a point, the mean energy flow through a closed surface (a), bounding a volume (v), is given by the integral $\oint \vec{S^*} \cdot \vec{n} da$. With $\vec{S^*}$ and its derivatives continuous in v, the divergence theorem yields

$$\oint \vec{S} \cdot \vec{n} da = \int_v \nabla \cdot \vec{S^*} dv. \tag{2}$$

From (1),

$$\nabla \cdot (\vec{E} \times \vec{\bar{H}}) = \vec{\bar{H}} \cdot (\nabla \times \vec{E}) - \vec{E} \cdot (\nabla \times \vec{\bar{H}}). \tag{3}$$

Upon defining the harmonic field vectors to be

$$\vec{E} = \vec{n_1} E_0 \epsilon^{-i\omega t} \text{ and } \vec{H} = \vec{n_2} H_0 \epsilon^{-i\omega t}, \tag{4}$$

Maxwell's laws yield

$$\begin{aligned} \nabla \times \vec{E} &= i\omega\mu\vec{H} \\ \nabla \times \vec{\bar{H}} &= (\sigma + i\omega\epsilon)\vec{\bar{E}}. \end{aligned} \tag{5}$$

From (2) through (5)

$$\int_v \nabla \cdot \vec{S^*} dv = \int_v \{ - 1/2\sigma \vec{E} \cdot \vec{\bar{E}} + i\omega(1/2\mu \vec{H} \cdot \vec{\bar{H}} - 1/2\epsilon \vec{E} \cdot \vec{\bar{E}}) \} dv. \tag{6}$$

Further, with $E_0=\tilde{E}_0$ and $H_0=\tilde{H}_0$, a good assumption at low frequencies and in the vicinity of the solenoid,

$$\int_v \nabla\cdot\vec{S}^*dv = -\,1/2\int_v \sigma E_0^2 dv + 1/2i\omega\int_v (\mu H_0^2 - \epsilon E_0^2)dv. \tag{7}$$

In the above group of equations the following meanings are attached to the symbols:

$\vec{n}_1, \vec{n}_2, \vec{n}$ = unit vectors,
E_0 = scalar intensity of $\vec{E}$,
H_0 = scalar intensity of $\vec{H}$,
$\omega = 2\pi$ times the frequency,
σ = electrical conductivity,
μ = magnetic inductive capacity,
ϵ = electric inductive capacity.

The mean energy flow described in equation (7) has its source in the solenoid. Associated with the variable part of the solenoid impedance (ΔZ) is an energy equal in amount to $\frac{1}{2} I_0^2\Delta Z$, where I_0 is the magnetizing current. This energy split into resistive and reactive components is expressed by

$$1/2I_0^2\Delta Z = 1/2I_0^2(\Delta R + i\Delta X) = 1/2I_0^2(\Delta R + i\omega\Delta L). \tag{8}$$

Setting (7) equal to (8) and neglecting $\epsilon E_0^2(\epsilon E_0^2 \ll \mu H_0^2)$, we obtain the expressions for the changes in the resistance and inductance of the solenoid.

$$\begin{aligned} \Delta R &= -\,I_0^{-2}\int_v \sigma E_0^2 dv \\ \Delta L &= I_0^{-2}\int_v \mu H_0^2 dv. \end{aligned} \tag{9}$$

For a volume of rock formation with constant values of μ and σ, recalling that ΔL actually refers to $\mu-\mu_0$, the expressions in (9) become

$$\begin{aligned} \Delta R &= -\,\Delta\sigma I_0^{-2}\int_v H_0^2 dv \\ \Delta L &= \mu_0\Delta\chi_m I_0^{-2}\int_v E_0^2 dv. \end{aligned} \tag{10}$$

From (10) the values of $\Delta R/\Delta\sigma$ and $\Delta L/\Delta\chi_m$ can be calculated for any volume selected.

The expressions in equations (10) are generally applicable for any model of the logging tool. The selection of a mathematical model simply specifies the values of the field vectors in space and is the second of four steps used in the

procedure to calculate the response curves for the logging tool. These steps are:

1. Section the response volume outside the tool case to permit practical use of the calculated results.

2. Select a mathematical model approximating the behavior of the logging tool.

3. Calculate the variation of the field vectors in space.

4. Calculate the response values $\Delta R/\Delta\sigma$ and $\Delta L/\Delta\chi_m$ for the selected sections of the volume.

Because of the obvious geometry of the borehole, long circular cylindrical shells coaxial with the borehole were used to determine the region of influence of the tool. The effect of layering in the rock formation can be derived from the use of circular cylindrical disks.

Once the model representing the magnet and its coil is selected, the Hertz polarization vector can be calculated and from it the vector and scalar potentials giving rise to the field vectors can be obtained. A simple model, chosen to reduce the numerical computation involved in evaluating equations (10), has provided solutions that check well with the experimental data.

The induction tool consists of a solenoid wrapped around a round bar. Current flowing in the solenoid induces a magnetic polarization in the bar. If $\vec{H}$ is the magnetic field in the bar, the magnetic polarization of the bar is described by

$$\vec{M} = \chi_m \vec{H}. \tag{11}$$

The vector $\vec{H}$ is determined from the Biot-Savart law, (applied to a statically energized solenoid). Along the axis of the solenoid of N turns per unit length, of length l_1, and diameter d, with a current I_0, assume

$$\vec{H} = \vec{i_3} N I_0 l_1 (l_1^2 + d^2)^{-1/2}. \tag{12}$$

For a coil of ratio $d/l_1 \ll 1$, from (11) and (12)

$$\vec{M} = \vec{i_3}\chi_m N I_0 = \vec{i_3} M. \tag{13}$$

Here, $\vec{i_3}$ is a unit vector along the Z-axis (the axis of the solenoid and bar).

The vector $\vec{M}$ is assumed reasonably to persist from one end of the bar to the other. It is this magnetic polarization that produces the field outside the case of the tool.

Since the eddy current in the bar reduces the penetration of the field into the bar, the value of χ_m in equation (13) can be approximated by assuming it to be equal to the ratio of the inductance values of the coil with and without the core,[3]

[3] R. Glasgow, *Principles of Radio Engineering*, McGraw-Hill (1936), p 51.

$$\chi_m \sim L_{\text{core}}/L_{\text{air}}. \tag{14}$$

It is advantageous to derive the field arising from the magnetic polarization by means of the Hertz vector (π^*). From equation (13) a single rectangular component of $\vec{M}$ is present; accordingly, it suffices to solve for π^*, corresponding to M, from the inhomogeneous differential equation

$$\nabla^2\pi^* - \mu_0\epsilon\frac{\partial^2\pi^*}{\partial t^2} - \mu_0\sigma\frac{\partial\pi^*}{\partial t} + M = 0. \tag{15}$$

The presence of a harmonic variation in $M(M = M_0\epsilon^{-i\omega t})$ leads to the inhomogeneous scalar wave equation

$$\nabla^2\pi^* + k^2\pi^* = -M, \tag{16}$$

where

$$k^2 = \mu_0\epsilon\omega^2 + i\mu_0\sigma\omega. \tag{17}$$

The values for the constants given in equation (17) are

$$\omega \leqq 2\pi 10^3 \text{ rad/sec},$$
$$\epsilon = 8.8 \times 10^{-12} \text{ farads/meter},$$
$$\mu_0 = 4\pi \times 10^{-7} \text{ henries/meter},$$
$$\sigma = 0.5 \text{ ohm/meter}.$$

Substitution of these values in equation (17) reveals that k^2 can be approximated by $i\mu_0\sigma\omega$.

The region of influence of the tool, beyond which less than 10 percent of the response to σ and χ_m of the formation arises, is well bounded by a sphere of radius one meter. Within this region the solution of π^* with $k=0$, can replace the solution with k given by equation (17), introducing no more than a few percent error. Thus,

$$\nabla^2\pi_0^* = -M_0 \tag{18}$$

where the zero subscripts denote removal of the harmonic variation ($\epsilon^{-i\omega t}$). The solution of (18) is given by

$$\pi_0^* = \frac{1}{4\pi}\int_v \frac{M_0}{R}\,dv, \tag{19}$$

where R is the distance from the observation point $P(r, \theta, Z)$ to the source point of integration $Q(r_1, \theta_1, Z_1)$.

$$R^2 = r^2 + r_1^2 - 2rr_1\cos(\theta - \theta_1) + (Z - Z_1)^2. \tag{20}$$

In solving (19) the magnetic polarization is confined only to that in the bar magnet, with that arising in the rock formation from χ_m assumed negligible.

Once $\vec{\pi_0}^*$ has been determined ($\vec{\pi}^* = \vec{\pi_0}^*\epsilon^{-i\omega t}$), the field vectors and their

potentials can be derived from

$$\begin{aligned}
\phi^* &= -\nabla\cdot\vec{\pi}^*, \\
\vec{A} &= \mu_0\nabla\times\vec{\pi}^* = \vec{A}_0\epsilon^{-i\omega t}, \\
\vec{H} &= \nabla\nabla\cdot\vec{\pi}^* = -\nabla\phi_0{}^*\epsilon^{-i\omega t}, \\
\vec{E} &= -\mu_0\frac{\partial}{\partial t}(\nabla\times\vec{\pi}^*),
\end{aligned} \tag{21}$$

where ϕ^* is the magnetic scalar potential and $\vec{A}$ is the vector potential.

The previous analysis indicates that the field potentials arising from the magnetic polarization of the solenoid are those of a statically magnetized bar with an $\epsilon^{-i\omega t}$ factor impressed on them.

Continuing the solution of equation (19) we find

$$\vec{\pi}^* = \frac{\vec{i}_3 M}{4\pi}\int_0^{2\pi} d\theta_1 \int_0^{r_0} r_1 dr_1 \int_{-l}^{l} [r^2 + r_1{}^2 - 2rr_1\cos(\theta-\theta_1) + (Z-Z_1)^2]^{-1/2} dZ_1, \tag{22}$$

where r_0 is the bar radius and $2l$ is the bar length. To evaluate (22) we assume $r \gg r_0$ so that the integration along Z_1 is approximately unchanged by setting $r_1 = 0$. The integration with respect to r_1 and θ_1 is then performed independently of that along Z_1 with the following result

$$\begin{aligned}
\vec{M}^* &= \frac{\vec{i}_3 M r_0{}^2}{4}\int_{-l}^{l}[r^2 + (Z-Z_1)^2]^{-1/2}dZ_1 \\
&= \frac{\vec{i}_3 M r_0{}^2}{4}\ln\{Z + l + [r^2 + (Z+l)^2]^{1/2}\} \\
&\quad - \ln\{Z - l + [r^2 + (Z-l)^2]^{1/2}\}.
\end{aligned} \tag{23}$$

Since the value of r_0 for the logging tool is one inch, the solution given in equation (23) would be valid for radial distances removed a few inches from the axis of the magnet, but would diverge from the correct solution as $r \to 0$. The singularities in the solution at $r = 0$ arise from the assumptions used in performing the integration of equation (22) and would not exist in exact evaluation of the same equation.

From equations (21) and (23) the field vectors and their potentials can be obtained, so that the expressions for $\Delta R/\Delta\sigma$ and $\Delta L/\Delta\chi_m$ given in equation (10), can be calculated. From equations (10) and (21)

$$\int_v H_0^2 dv = \int_v (\nabla \phi_0^*)^2 dv$$
$$\int_v E_0^2 dv = \int_v \omega^2 A_0^2 dv = -\omega^2 \mu^2 \int_v (\nabla \times \vec{\pi}_0^*)^2 dv. \tag{24}$$

The volume integrals, given above, can be transformed to surface integrals as follows,

$$\int_v (\nabla \phi_0^*)^2 dv = \oint_a \phi_0^* \nabla \phi_0^* \cdot \vec{n} da$$
$$\int_v (\nabla \times \vec{\pi}_0^*)^2 dv = \oint_a \vec{\pi}_0^* \cdot (\vec{n} \times \nabla \times \vec{\pi}_0^*) da. \tag{25}$$

By sectioning the response volume into the infinitely long circular cylindrical shells, mentioned previously, ($r=r_1$, $r=r_2$, $r_2>r_1$), $\vec{n}da=\vec{i}_1 r dZ d\theta$, for which

$$\int_v (\nabla \phi_0^*)^2 dv = 2\pi r \int_{-cs}^{cs} \phi_0^* \nabla \phi_0^* \cdot \vec{i}_1 dZ \Big]_{r=r_1}^{r=r_2}$$
$$\int_v (\nabla \times \vec{\pi}_0^*)^2 dv = 2\pi r \int_{-cs}^{cs} \vec{\pi}_0^* \cdot (\vec{i}_1 \times \nabla \times \vec{\pi}_0^*) dZ \Big]_{r=r_1}^{r=r_2}. \tag{26}$$

The contribution to the integrals on the two surfaces, $Z=\pm\infty$, is zero, since the integrals vanish as $1/Z^2$. If the two integrals in (26) are calculated for

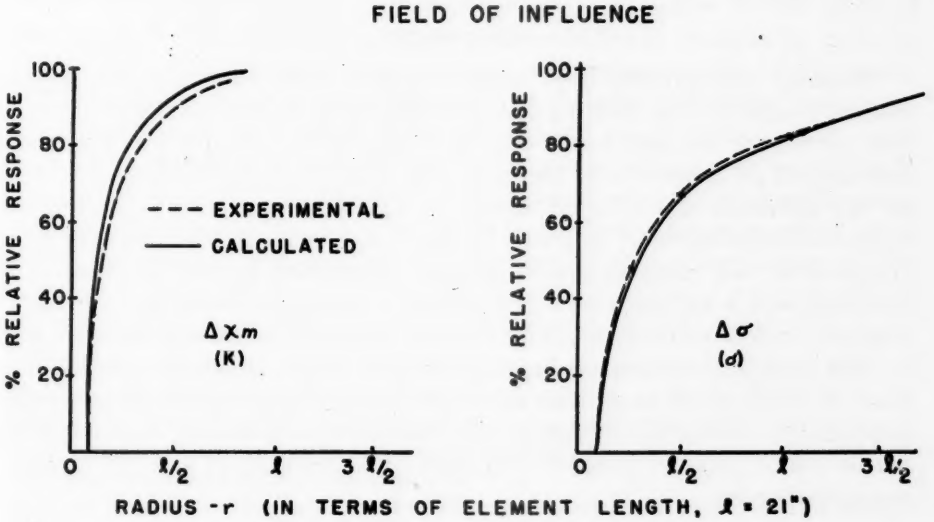

FIG. 18. Calculated and experimental response curves illustrating the difference in depth of investigation for the two components.

$r=r_1$, $r=r_2=\infty$ the non-zero contribution occurs on the surface $r=r_1$, since the integral vanishes as $1/r$ for $r=\infty$. We can define $(\Delta R/\Delta\sigma)_r$ and $(\Delta L/\Delta\chi_m)_r$ to be the response values occurring for an infinitely long cylindrical shell of inner radius, r, and of infinite outer radius. Thus, for example, the response value, $\Delta R/\Delta\sigma$, a shell of thickness, $\Delta r=r'-r$, can be found directly from

$$(\Delta R/\Delta\sigma)_{\Delta r} = (\Delta R/\Delta\sigma)_r - (\Delta R/\Delta\sigma)_{r'}. \tag{27}$$

If we let $r=c$, the radius of the case of the induction tool, and plot the relative response values for $\Delta r=r-c$, based on a 100 percent response at $r=\infty$, versus the radial distance r, we obtain the two curves shown in Figure 18. The experimental values for both components, taken from Figure 3, are also shown, and the experimental and theoretical curves compare well for both components. Good agreement also exists between the absolute values of the theoretical and experimental response values:

	$(\Delta R/\Delta\sigma)_c$	$(\Delta L/\Delta\chi_m)_c$
Calc.	2.12×10^{-1} ohms/(ohm meter)$^{-1}$	4.50×10^{-8} henries/$(\Delta\chi_m\times10^6)$
Exp.	2.46×10^{-1} ohms/(ohm meter)$^{-1}$	3.62×10^{-8} henries/$(\Delta\chi_m\times10^6)$

Although the present calculations do not include effects of layering in the formation, the expressions in equation (25) can be used equally well on disks, representing layers, with a one-dimensional integration still being sufficient.

The method derived above is applicable to more complicated models of the bar magnet. Numerical calculation of the different potentials can be employed; following this, the use of equations (25) and (10) will result in determination of both response values.

CONCLUSIONS

Magnetic susceptibility logs exhibit excellent reproducibility. The logging speed is limited only by hoisting and recording equipment. Since this is an induction instrument the instrument will log in any conventional oil or water base mud as well as in open hole. Magnetic susceptibility logs provide control data for interpretation of surface of airborne magnetometer surveys by telling the magnitude and extent of magnetic bodies. Since magnetic susceptibility is an independent rock property and is primarily controlled by the iron content of the rock, such a log provides a new means for geologic correlation. The use of magnetic tracers in drilling muds for marking permeable zones appears promising.

The total field instrument has been limited in use. It seems to have raised about as many questions as it has answered. The total field consistently decreases inside highly susceptible formations. An evaluation of formation remanent magnetism can be obtained from the total field log in conjunction with the magnetic susceptibility log.

A MAGNETIC STUDY OF THE SPAVINAW GRANITE AREA, OKLAHOMA*

JULIAN HAWES†

ABSTRACT

Detailed magnetic maps over three of the four Spavinaw Granite outcrops are presented. These combined with laboratory measurements of the direction and intensity of the permanent magnetization and susceptibility measurements reveal the relative importance of permanent and induced fields at short distances from the granite. An air magnetic survey at 675 feet above the granite indicates the elimination of permanent field effects at that height.

The size of the air magnetic anomaly when compared with the magnitude of folding known to be present in the Spavinaw anticline suggests strongly that a petrologic contrast with accompanying susceptibility contrast exists in the basement here. This could readily be interpreted as evidence of the intrusive nature of a local igneous body forming the core of the anticline, although it does not afford evidence of the date of intrusion.

I. INTRODUCTION

A. *Aim of the Study*

The magnetism of igneous rocks has been only sketchily defined in quantitative terms.[1] At least two purposes would be served by a detailed study of the magnetic properties of igneous rocks.

The first purpose is the definition of the magnetic units (volumes having remanent magnetization uniform in direction and intensity and uniform susceptibility) in size, shape, and attitude. Definition of these units might yield information of considerable value concerning some processes active in the origin of igneous bodies. This information might well be yielded in terms of the patterns of these units as a group and in terms of internal patterns exhibited individually.

The second purpose is concerned with the problem of defining in terms of depth, size, shape, and attitude those igneous and metamorphic bodies, made up of one or more magnetic units, creating magnetic fields strong enough to be measured by conventional instruments through thicknesses of cover (sedimentary rocks usually) varying up to thousands of feet. Preparation of magnetic maps (ordinarily of the vertical, horizontal, or total intensity) over large areas permits definition of these attributes with varying degrees of accuracy by several techniques. One of the most commonly used of these methods is that of model[2] match-

* Manuscript received by the Editor July 2, 1951. Presented before the Geophysical Society of Tulsa September 13, 1951.

Most of the material used here was presented to the Department of Geology, Harvard University, as a thesis in partial fulfillment of the requirements for the Ph.D.

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[1] J. McG. Bruckshaw, and E. I. Robertson, "The Magnetic Properties of the Tholeiite Dykes of North England," *Monthly Notices Royal Astr. Soc., Geoph. Sup. No. 8* (1949), 308–320.

[2] Victor Vacquier et al., "Interpretation of Aeromagnetic Maps," Geol. Soc. Am. Memoir 47 (Nov. 7, 1951).

ing, in which the assumption is usually made that the field to be matched is one induced by the earth's normal field. This assumption ignores the effect of remanent magnetism which in certain rocks is known to exceed in strength the induced magnetism by a factor of ten or more. Possibility of important error exists under these conditions due to the difference between the assumed direction of polarization and the actual one. This is the case largely due to lack of specific knowledge of the direction, strength, and uniformity of remanent polarization.

The present study defines the direction, strength, and uniformity of the remanent field in a specific igneous body and compares it to the induced field at two levels above the body. In the phase of the investigation dealing with the induced field a limited investigation was also made of the relation between susceptibility and the volume proportion of magnetite in this body.

B. *Geographic and Geologic Setting of the Area*

Igneous rock of granitic composition outcrops in four separate areas (numbered from one to four here, number one being northernmost) near the town of Spavinaw, Sec. 15, T. 22 N, R. 21 E, Mayes County, northeastern Oklahoma. About 80 miles to the northwest in Woodson County, Kansas, is the nearest adjacent outcrop of igneous rock; this is a granite.[3,4]

The Spavinaw area, situated on the northwest flank of the Oklahoma portion of the Ozark Uplift, exhibits a gentle regional dip to the northwest. The geologic sequence in the vicinity of Spavinaw is given in Table I below:

TABLE I

STRATIGRAPHIC SUCCESSION NEAR SPAVINAW, OKLAHOMA

System	Formation	Approximate Thickness
Mississippian	Boone Limestone	0–300 feet
Devonian-Mississippian	Chattanooga Shale	61 feet
Cambrian-Ordovician	Arbuckle Dolomite	0–100 feet or more
Unknown	Spavinaw Granite	Unknown

An important hiatus consisting of part of the Ordovician, all of the Silurian, and part of the Devonian is shown between the Arbuckle Limestone and the Chattanooga Shale.

A topographic relief approximating 300 feet exists in the area. Slopes are generally wooded with the clearest exposures confined to stream beds.

Seven miles west of the Spavinaw granite exposures, the Seneca Fault trends N 50° E. The granite occupies the axis of an anticline trending N 30° E.

South of the southernmost granite exposure (called outcrop number 4 here),

[3] W. E. Twenhofel, "Intrusive Granite of the Rose Dome, Woodson County, Kansas," *Geol. Soc. Am. Bull., Vol. 37* (1926), 402–412.

[4] W. H. Twenhofel, and Bernard Bremer, "An Extension of the Rose Dome Intrusive, Kansas," *Am. Assoc. Petr. Geol. Bull., Vol. 12* (1928), 757–762.

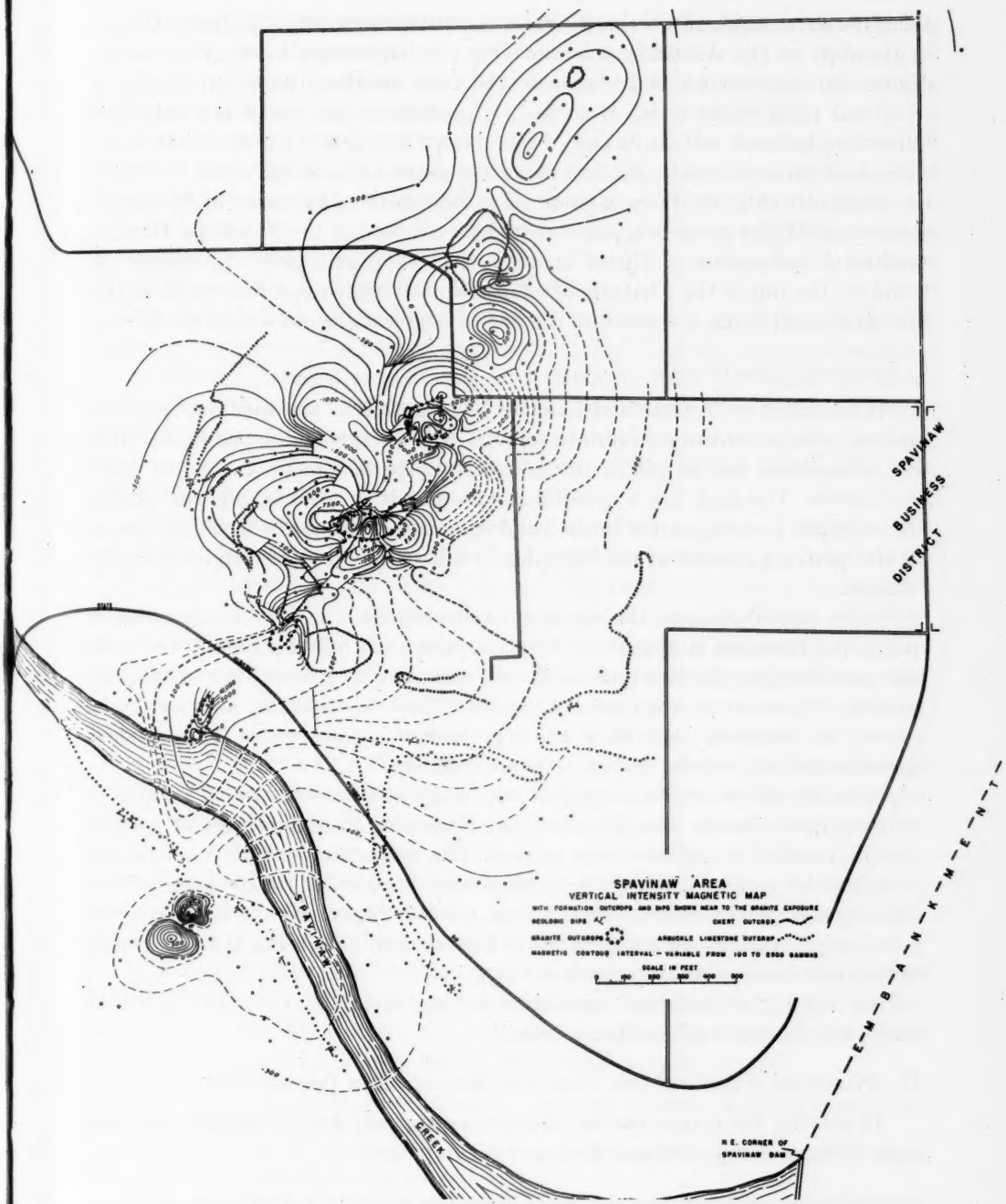
SPAVINAW BUSINESS DISTRICT
SPAVINAW AREA
VERTICAL INTENSITY MAGNETIC MAP
WITH FORMATION OUTCROPS AND DIPS SHOWN NEAR TO THE GRANITE EXPOSURE
GEOLOGIC DIPS
CHERT OUTCROP
GRANITE OUTCROPS
ARBUCKLE LIMESTONE OUTCROP
MAGNETIC CONTOUR INTERVAL - VARIABLE FROM 100 TO 2500 GAMMAS
SCALE IN FEET
0 100 200 300 400 500
SPAVINAW CREEK
N.E. CORNER OF SPAVINAW DAM
E M B A N K M E N T

FIG. 1. Vertical Intensity Magnetic map, Spavinaw Area.

along the south bank of Spavinaw Creek, the anticlinal reversal is clearly shown in the dips of the Arbuckle dolomite (Fig. 1); these dips vary up to seven degrees in steepness on both flanks of the fold. Southeastward dip, giving a structural relief of the order of 90 feet, is present on the top of the Arbuckle Formation between the south end of Spavinaw Dam and the crest of the anticline, a distance of about 2,700 feet along the south bank of Spavinaw Creek to the northwest (Fig. 1). From a point 2,250 feet north of the town of Spavinaw along State Highway 20 to a point near the south end of the Spavinaw Dam, a southward component of dip of about 44 feet (approximately one degree) is found on the top of the Chattanooga formation. Within 1,000 feet north of the first mentioned point, a northward dip of five degrees is found within the Boone.

C. *Character of the Granite*

As described by Tolman and Landes,[5] "The granite is red, medium to coarse grained, with a tendency to seriate texture. The average grain size is less than five millimeters, but in places the feldspars range in size up to one or more centimeters. The rock has a syenitic aspect, but it is actually high in quartz, although this is not apparent in the hand specimen owing to the fact that almost all the quartz is present as micrographic or micrograno phyric intergrowths with feldspar.

Under the microscope the exceptional development of the intergrowths of quartz in orthoclase is apparent. Albite is present in minor amounts and does not show intergrowths with quartz. Hornblende, the only primary ferromagnesian mineral, is present in very small amounts. There is, however, an exceptional amount of magnetite. Apatite is also a prominent accessory and the secondary minerals epidote, sericite, and chlorite are common."

With the aid of an Alnico magnet, the magnetite present in nine samples of the Spavinaw Granite was separated (see Appendix A). An average of 1.8 percent by volume of magnetite was present. The magnetite percentage, compared to figures by volume given by Johannsen[6] and Stearn[7] for the average granite, 0.99 and 0.90 percent respectively, is high, possibly explaining the high remanent polarization found in the granite and the high susceptibility. The average density of the rock from 97 measurements is 2.655.

No banding or preferred orientation for any minerals were noted in macroscopic examinations of granite specimens.

D. *Discussion of Induced and Remanent Magnetism in Igneous Rocks*

In general, the magnetization of igneous rocks may be divided into two parts —an induced component and a remanent component.

[5] Carl Tolman, and K. K. Landes, "Igneous Rocks of the Mississippi Valley Lead-Zinc Districts," *Geol. Soc. Am. Special Paper 24* (1939), 77–78.

[6] Albert Johannsen, *A Descriptive Petrography of the Igneous Rocks, Vol. II* (1932), pp. 185–189.

[7] N. H. Stearn, "A Background for the Application of Geomagnetics to Exploration," *A.I.M.E., Vol. 81* (1929), 315–344.

The induced component is that portion of the total magnetization which is dependent upon the susceptibility (or ease of magnetization) and the strength of the surrounding magnetic field. The equation $I = SH$ expresses the relationship where I is induced magnetization, H is field, and S is susceptibility.

The remanent component is the other portion of the total magnetization which is characterized by its relative independence of surrounding fields. It is unaffected by changes in orientation with respect to the earth's field or by a complete shielding from all fields. It may be changed, however, by being placed in a sufficiently strong field. Likewise, it is affected in varying degree by heat, pressure, chemical disintegration, and time.[8,9]

Apparently both induced and remanent components are dependent principally upon the amount of magnetite present, though, in some cases, such minerals as pyrrhotite, ilmenite, franklinite, and hematite may contribute to them. According to Nagata,[10] a texture in which the magnetite is distributed uniformly in small grains is more conducive to a high ratio of remanent to induced intensity than one in which it occurs as a few large grains. The absolute effects of texture differences are not clear from Nagata's account.

Large remanent magnetization may be acquired in igneous rocks in the process of cooling through the Curie Point (580°C. to 720°C.) in a field comparable to the earth's as shown by Nagata.[11] His experiments on a few selected samples of basalt and andesite show that under these conditions remanent magnetizations from two to 93 times as large as the magnetization due to induction in the normal earth's field may be acquired. Nagata's work indicates that the remanent magnetization acquired at high temperatures is proportional to the inducing field as long as the latter is of the order of 1.5 gauss or less.

Haalck,[12] in reviewing the work of various authors, shows that experimental results are in general agreement with those of Nagata as to the origin of remanent magnetization in igneous rocks. He suggests, without experimental or other evidence to demonstrate their effectiveness, that stresses and thermoelectric currents may have created, in solidifying igneous bodies, magnetic fields differing in direction from the earth's normal field, these directions determining locally the direction of the remanent polarization in the solidified body.

It is apparent from the foregoing that the chemical composition of an igneous rock is not the only critical factor in determining its magnetization. The manner in which the iron is combined, the texture, the uniformity of orientation of the polarized grains and its thermal history are likewise very important.

[8] G. L. Taylor, and D. H. Reno, "Magnetic Properties of Granite Wash and Unweathered Granite," *Geophysics, Vol. XIII*, No. 2 (1948), 163–181.

[9] J. G. Koenigsberger, "Residual Magnetism and the Measurement of Geologic Time," *Inter. Geol. Cong. Rept. of 16th Session, Vol. 1* (1933), 225–231.

[10] T. Nagata, "Mode of Causation of Thermo-Remanent Magnetism in Igneous Rocks," *Bull. Earthquake Research Inst., Tokyo University, Vol. XIX*, pt. 1 (1941), 54.

[11] T. Nagata, op. cit., pp. 51–72.

[12] H. Haalck, *Der Gesteinsmagnetismus;* published by J. W. Edwards, Ann Arbor, Mich. (1945), 25–35, 70–77.

II. FIELD AND LABORATORY METHODS

A. *Vertical Intensity Surveys*

An Askania Vertical Magnetometer with a scale constant of 172 gammas per division was used to make detailed vertical intensity magnetic maps on a scale of one inch to twenty-five feet over three of the four outcrops.

On a scale of one inch to one hundred feet, a less detailed vertical intensity map is included. This map centers on the four granite outcrops, but extends beyond them on the north and south, covering an area about 4,800 feet long by 1,000 feet wide (Fig. 1). Structure in the sediments immediately adjacent to the granite is shown by dip symbols on this map, and the outcrop patterns nearest to the igneous exposures are shown.

All horizontal control for mapping was obtained through use of a plane table and alidade.

B. *Vertical Gradient of Vertical Intensity Survey*

It is possible to obtain measurements of the vertical gradients over principal anomaly centers since these are unusually large. This was done for the vertical intensity by reading the instrument once with tripod legs contracted and a second time with the legs extended to the limit, giving an average change in instrument height of approximately 20 inches. In this manner, gradients were obtained over the centerpoints of 14 anomalies—7 highs and 7 lows.

C. *Total Intensity Survey*

The total intensity, which is the vector sum of the vertical and horizontal intensities, was mapped through use of the airborne magnetometer.[13]

An air magnetic map made from data collected 1,400 feet above sea level, or an average of 675 feet above the terrain, covers approximately fifteen square miles, centering on the granite outcrops. A flight-line spacing varying from 7,400 feet to 600 feet was used. Two profiles 1,900 feet above sea level, 500 feet higher than the lower lines, were flown across the area (Figs. 2, 3).

D. *Sampling Technique*

Samples of the granite were taken for laboratory study in an effort to establish the relative importance of induced and remanent magnetization.

Anomaly centers were selected for sampling wherever good exposures of granite in place coincided with them. This was done because whatever conditions of magnetization created them might be at a maximum in or near the anomaly centers. Boulders which had turned or rolled were avoided wherever they could be recognized since the directions shown by the remanent magnetization in them would have no necessary relation to the original direction.

[13] Gary Muffly, "The Airborne Magnetometer," *Geophysics, Vol. XI*, No. 3 (1946), 321–334 (describes the principles upon which this instrument operates).

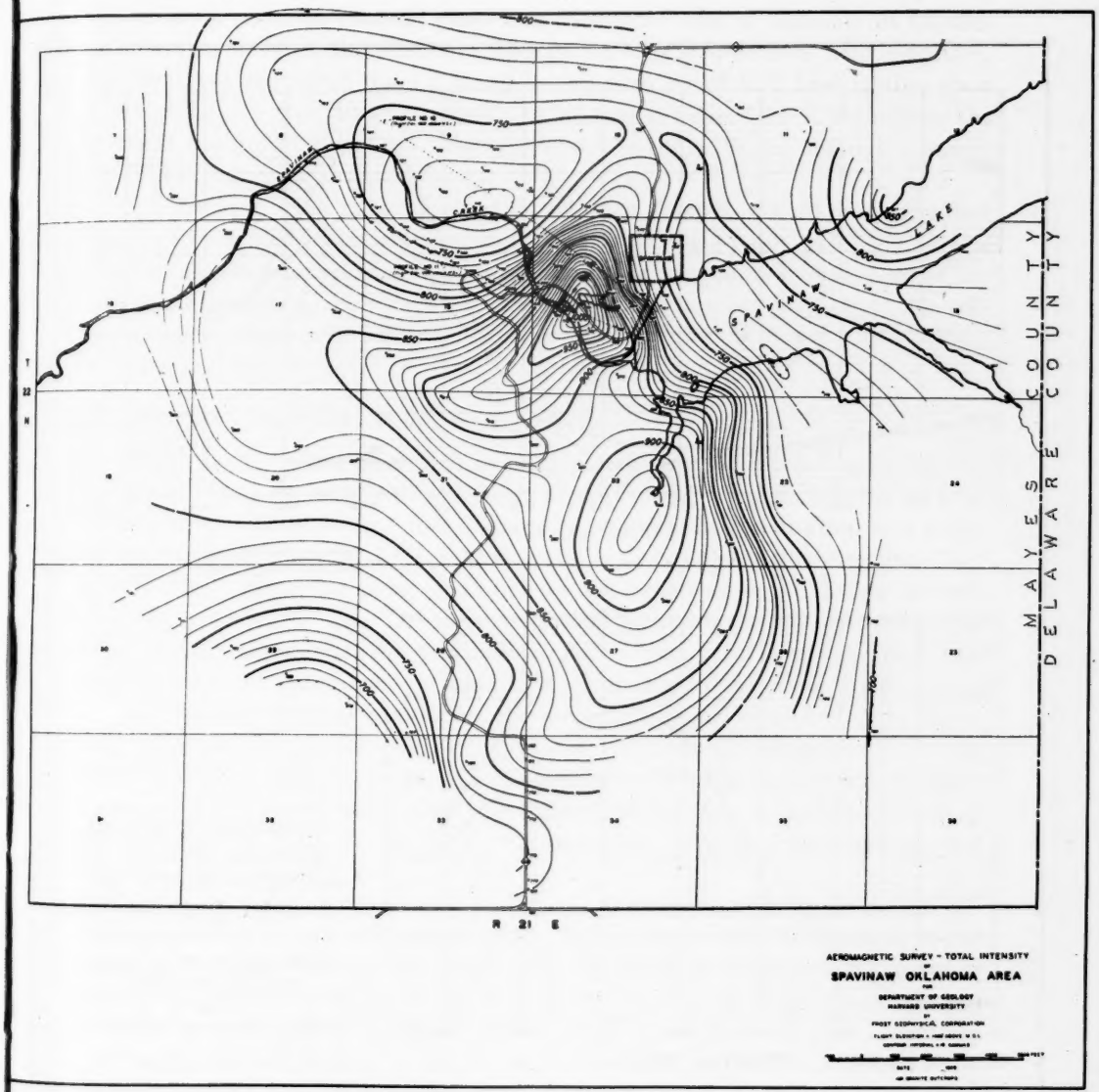

FIG. 2. Aeromagnetic Survey, Total Intensity, Spavinaw Area.

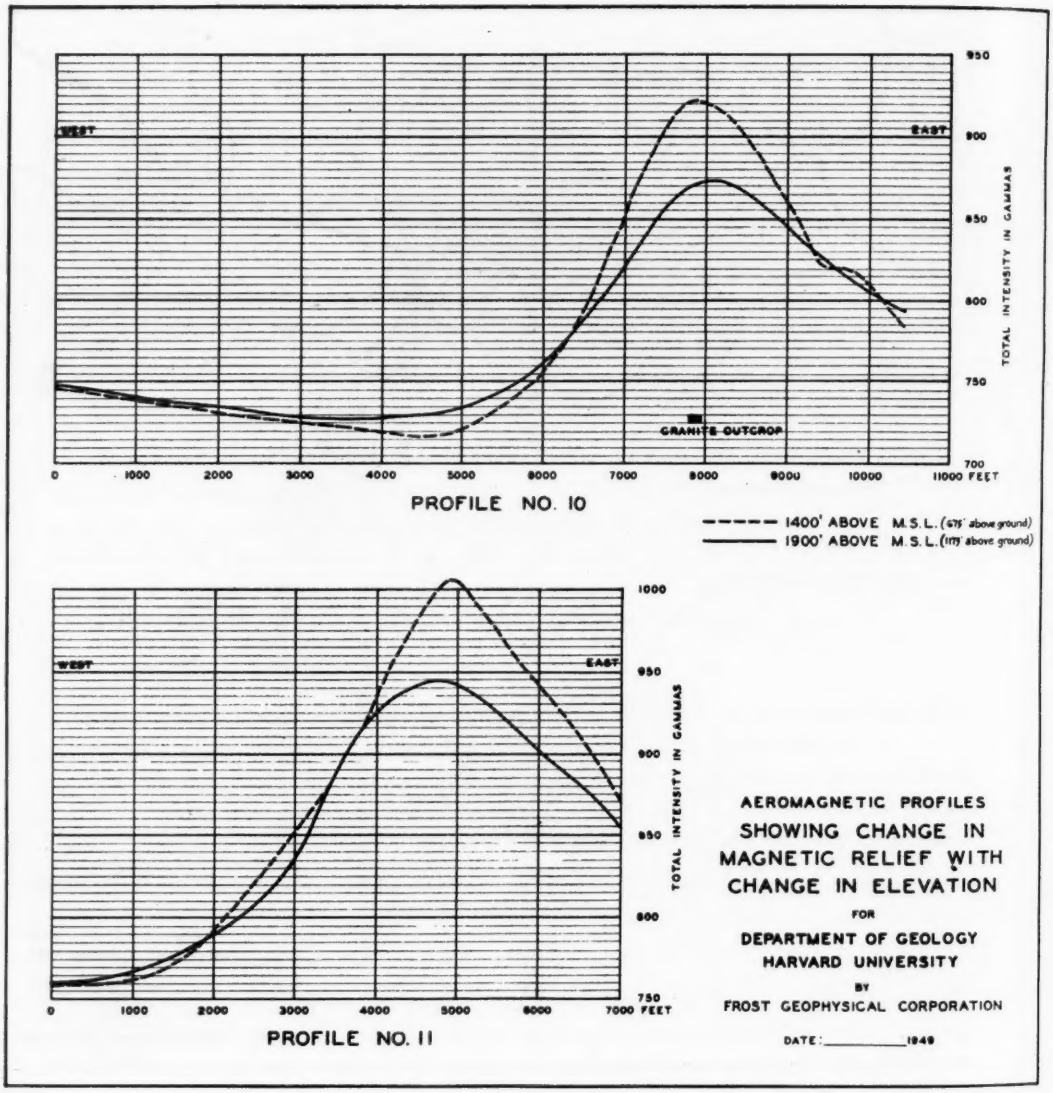

FIG. 3. Aeromagnetic profiles, Spavinaw Area.

For the physical procedure of taking samples, a hand-operated utility drill, driven by a portable 110-volt generator, was fitted with a diamond bit capable of cutting a one-inch diameter core three inches long. For efficient field operation, the drill was supported upon a stand having a 16 by 18 inch base resting upon four adjustable feet. Pressure upon the bit was regulated by a lever from the vertical column of the stand through the drill handle. Water through a swivel removed cuttings and cooled the bit.

To secure a geographic orientation on each sample, a cord was stretched from a tree, whose position was mapped, to the sampling point, guiding a narrow line which was painted with nail polish across the area to be drilled. Due to unsuitable equipment, the earliest samples were less than one inch long; this was corrected so that later samples were two inches long or longer except where jointing occurred.

E. *Remanent Magnetization and Susceptibility*

The original cylinders, drilled from field locations corresponding to vertical intensity locations, were cut into cubes approximately 0.65 inch along an edge with a copper blade tipped with diamonds. The original orientation was maintained with the horizontal plane having one edge parallel to the direction "X," the direction from the point of coring to the orienting point, a tree in each case. Directions "Y" and "Z" were in vertical planes of the cube, forming with "X" a set of three mutually perpendicular axes (Fig. 4). The orientations used in the remanent magnetometer runs were determined from these three axes.

Measurements of the component of remanent moment in each of three mutually perpendicular planes, XY, YZ, and XZ, furnished a total of six quantities, three moments and three angles. The angle in the XY plane (which is horizontal) between X and the moment gives the azimuth of the total moment with respect to X. Since X is a known direction, the geographic azimuth of the total moment may be readily found.

It is easily possible to solve for the dip of the moment with respect to the XY plane, which is always horizontal. Since, due to characteristics inherent in the remanent magnetometer, the angles are probably measured with somewhat greater accuracy than the moments, it is desirable to use only angles (no moments) in solving for the dip of the total moment. Any two angles will yield a solution for the dip. The three angles measured furnish three combinations of two each, giving three solutions. The sterographic projection, used as described by Bucher,[14] permits speedy solution from each of the three pairs and convenient averaging of the results from the triangle of error shown on the projection.

Errors of four to five degrees may easily have been present in many of the field orientations with additional errors being introduced in cutting, as cube faces frequently were 88 to 92 degrees apart instead of 90 degrees. It is felt that

[14] W. H. Bucher, "The Stereographic Projection, a Handy Tool for the Practical Geologist," *Journ. Geol., Vol. LII*, No. 3 (1944), 191–212.

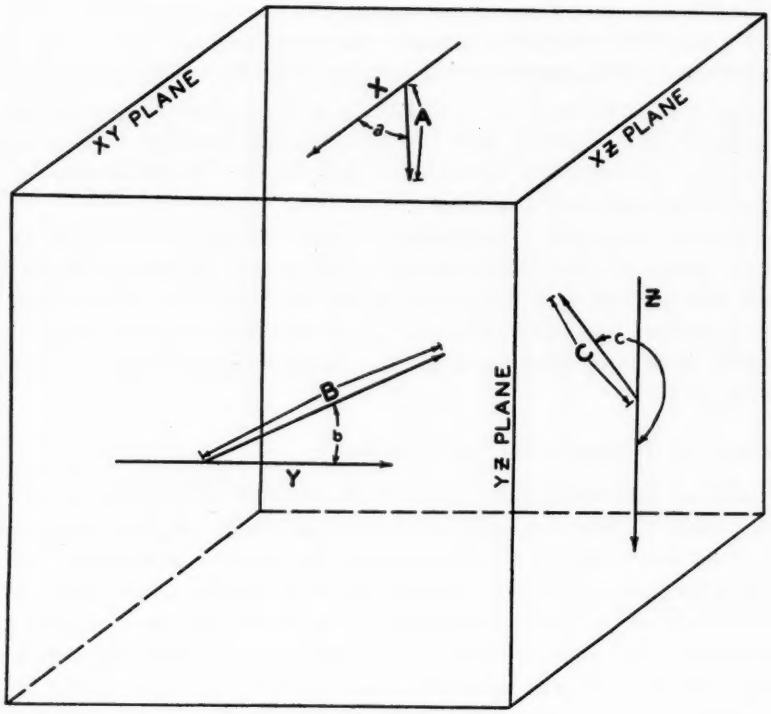

FIG. 4. System of reference axes for determining remanent magnetization intensity and direction.

the remanent azimuth and dip, in general, are not in error by more than 10 degrees, which for present purposes is not significant. Remanent intensity measurements were affected principally by errors in cutting and in calibration. They are estimated to be accurate within ten percent, for the most part.

The total moment may conveniently be found from the formula:

$$M = \sqrt{\frac{A^2 + B^2 + C^2}{2}} \text{ (appendix } B\text{)}$$

where A, B, and C are components of moment in the XY, YZ, and XZ planes, respectively.

Remanent directions and moment were measured by a special magnetometer of the type described in a paper by Johnson and others.[15] Essentially, the cubes of granite were rotated above a pickup coil, once on an axis perpendicular to the *XY* plane (Fig. 4), once on an axis perpendicular to the *YZ* plane, and once on an axis perpendicular to the *XZ* plane. The cube, in a holder at the end of a shaft, is simply turned after each rotation to the appropriate new positio .. In each position, the component of the total moment in the plane perpendicular to the axis of rotation is measured, this being proportional to the voltage created in the pickup coil. Phase of the wave from the granite cube is, in the same operation, compared to that of an introduced signal of known phase to determine the direction of the component moment.

Susceptibility was measured by a four-arm bridge consisting of a fixed resistor, a variable resistor, a fixed inductor, and a combined fixed inductor and variable resistor. The fixed inductor, which has a field of two gauss, is the pickup coil. The sample is placed in the core of this inductor, the percentage change of inductance being proportional to the susceptibility and to the change of the appropriate resistor.

A glass tube of approximately five cc volume, containing particles of the general diameter range 0.10 inch to 0.01 inch, was used for each measurement. The density of the material in the tube compared to the true rock density furnishes a factor to use in finding the susceptibility in cgs units per cubic centimeter.

III. RESULTS OBTAINED FROM MEASUREMENTS

A. *Vertical Intensity*

The three vertical intensity maps (Figs. 5, 6 and 7), covering outcrops 1, 2, and 4, exhibit high magnetic relief and very steep horizontal gradients. In the extreme cases, the horizontal gradient is 9,000 gammas in 10 feet. Both magnetic high and low anomalies tend to be roughly circular or elliptical in outline, varying in size from about 25 feet along the shortest minor axis to about 150 feet along the longest major axis. Though no regular pattern of alternation from highs to lows is evident, there are apparently as many of one as of the other.

Figure 1 (open circles on this plate show magnetometer station locations) of the vertical magnetic intensity in the general area of all four granite outcrops, indicates that the maximum relief and the maximum horizontal gradients are to be found upon the bare granite. Though in local areas it contains magnetic lows, the northeastward trending granite axis is, in general, a magnetic high axis. The two small, sharp, and circular magnetic highs near the south end of the map may be considered extensions of the granite axis southward beyond its outcrop. Likewise, the highs to the north of the outcrops almost certainly indicate an extension of the granite axis northward.

[15] E. A. Johnson, Thomas Murphy, and P. F. Michelsen, "A New High Sensitivity Remanent Magnetometer," *Rev. of Sci. Int., Vol. 20*, No. 6 (1949), 429–434.

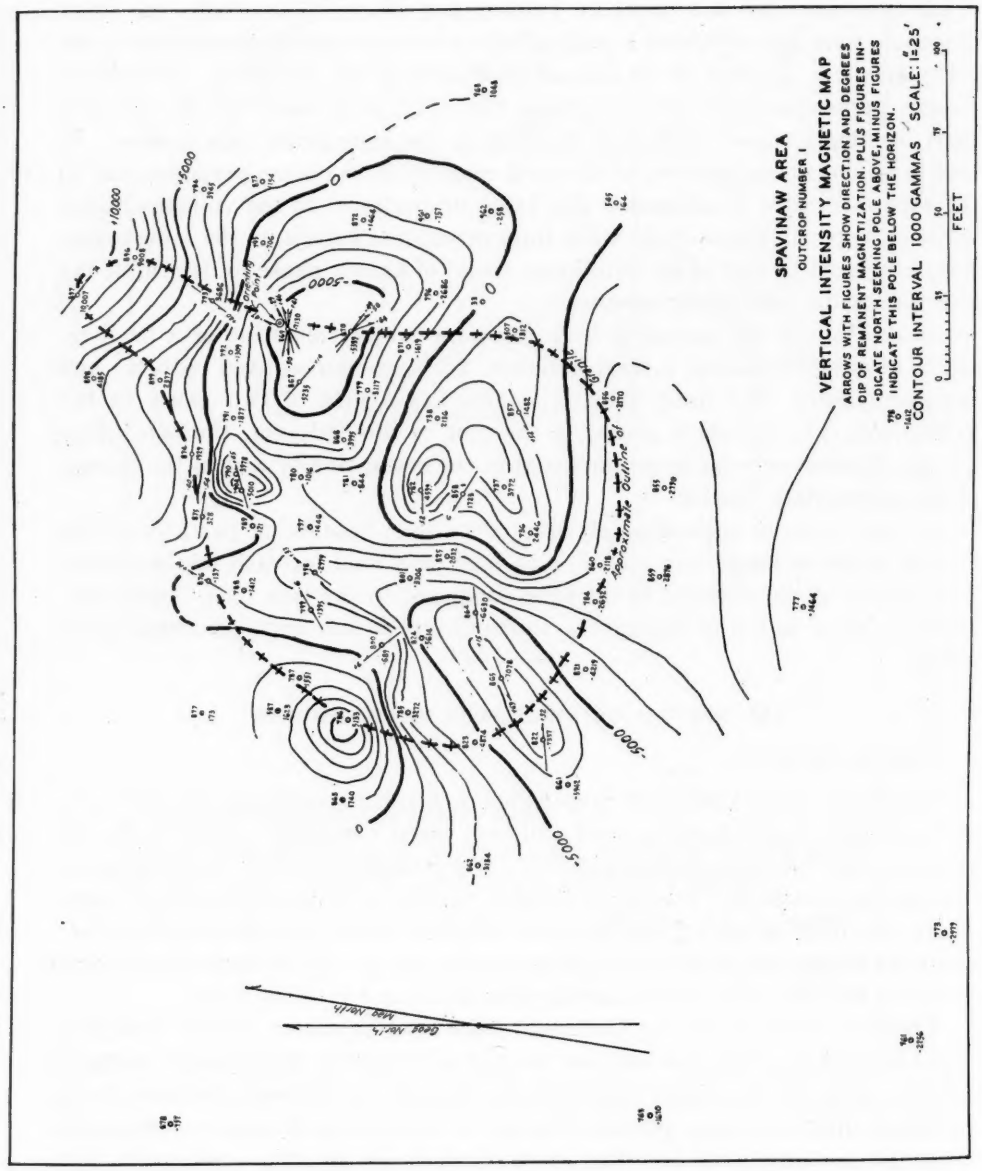
SPAVINAW AREA
OUTCROP NUMBER 1
VERTICAL INTENSITY MAGNETIC MAP
ARROWS WITH FIGURES SHOW DIRECTION AND DEGREES DIP OF REMANENT MAGNETIZATION. PLUS FIGURES INDICATE NORTH SEEKING POLE ABOVE, MINUS FIGURES INDICATE THIS POLE BELOW THE HORIZON.
CONTOUR INTERVAL 1000 GAMMAS SCALE: 1=25'
0 25 50 75 100
FEET
Approximate Outline of
Geom. North
Mag. North
-5000
-10000
-15000

FIG. 5. Vertical Intensity Magnetic map, Outcrop No. 1, Spavinaw Area.

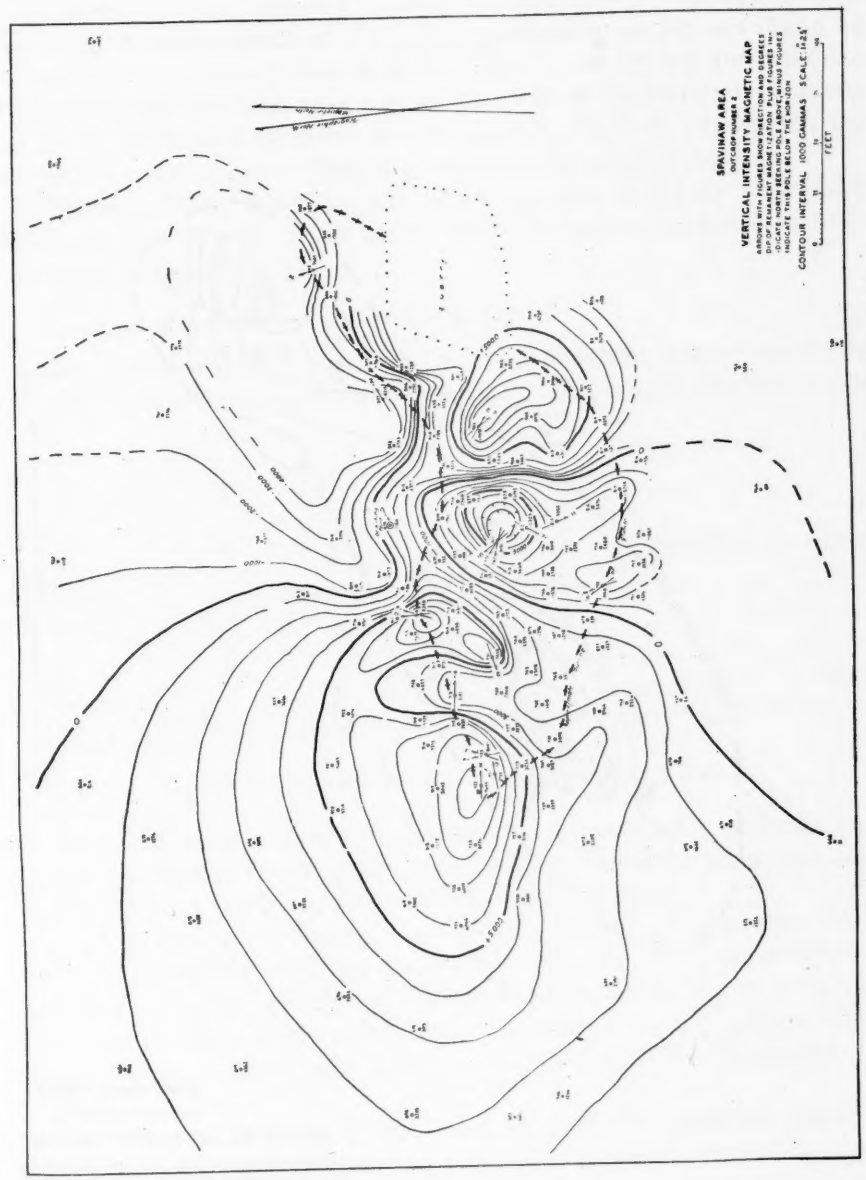

FIG. 6. Vertical Intensity Magnetic map, Outcrop No. 2, Spavinaw Area.

FIG. 5. Vertical Intensity Magnetic map, Outcrop No. 1, Spavinaw Area.

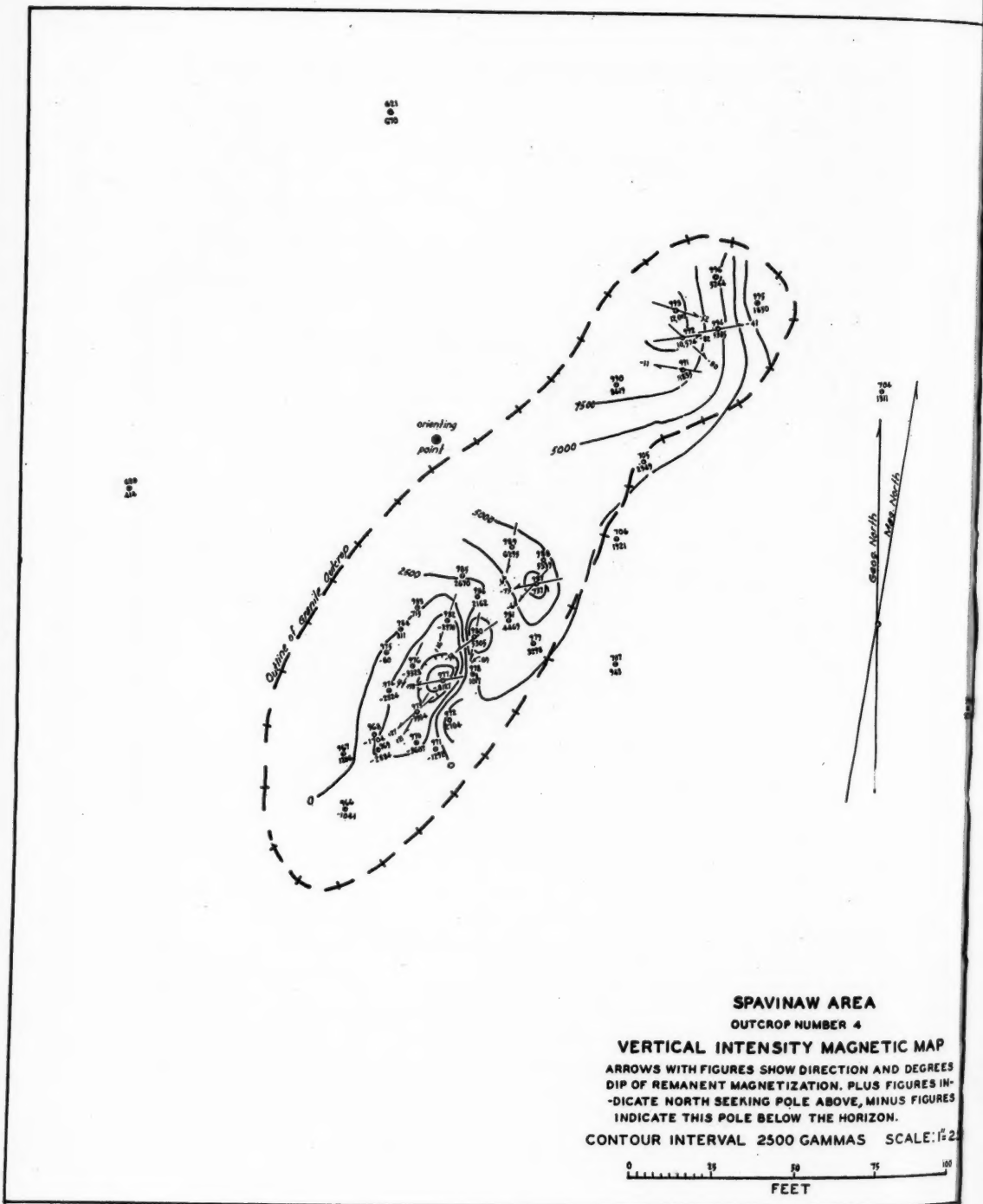

FIG. 7. Vertical Intensity Magnetic Map, Outcrop No. 4, Spavinaw Area.

B. *Total Intensity*

In terms of total intensity, a relief of approximately 300 gammas and a maximum horizontal gradient of about 70 gammas in 500 feet are shown by the air magnetic map (Fig. 2) made from data taken about 675 feet above the terrain. The offset of the total intensity high to the south of the four granite outcrops is normal for induced magnetism in this latitude, although admittedly, lack of control for contouring may affect its position several hundred feet.

The two profiles, flown 500 feet above the level of the air magnetic map, show reduction in relief of the anomalies at the higher elevation, as well as a smoothing of them (Fig. 3).

C. *Remanent Magnetization and Susceptibility*

Ninety-seven cubes were measured with the remanent magnetometer. Dips of the total moment varying from +83 to −83 degrees (the plus sign indicating

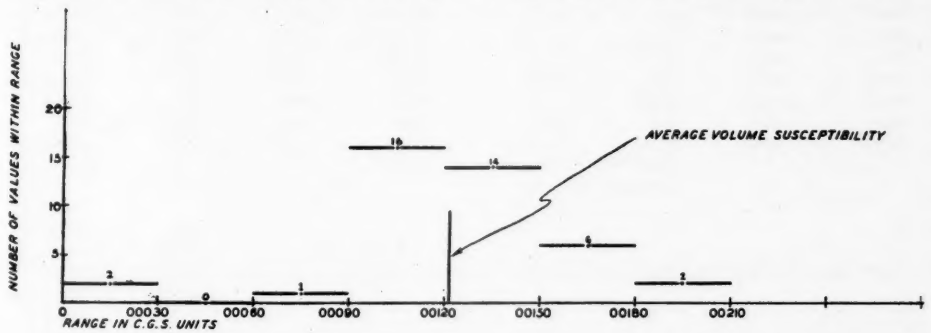

FIG. 8. Frequency distribution of volume susceptibilities.

the north-seeking pole above the horizon) were found with azimuths varying through 360 degrees. It should be noted that many cores were taken near anomaly centers and may, therefore, yield somewhat unusual values.

Susceptibility was measured on 41 samples made from chips from the cores used in the study of remanent polarization. Susceptibility values varied from 0.00028 to 0.00198 in cgs units per cubic centimeter, a ratio of 7 to 1, the average being 0.00121. For a single observation, the probable error is 0.00022, while for the mean, it is 0.00003. Figure 8 shows a frequency distribution plot for volume susceptibility.

The values in Table II, giving remanent intensity (remanent moment per unit volume), are derived from the values for the total moment by dividing them by the appropriate sample volumes. These values are separated into classes depending upon whether the north-seeking arrow points above or below the horizon. The average values for each of the two cases differ by about 11 percent. These averages are made from values ranging from 0.0010 to 0.1767, a ratio of 177 to 1, the average of all values being 0.0175.

TABLE II

I_r = REMANENT INTENSITY (MOMENT PER UNIT VOLUME)

North-Seeking Pole Directed							
Above the Horizon				Below the Horizon			
No.	I_r	No.	I_r	No.	I_r	No.	I_r
714	.0027	812C	.0060	714B	.0052	869_2B	.0037
718	.0194	822	.0280	714C	.0012	869_2C	.0016
718_2	.0202	822B	.0235	720	.0470	869S	.0022
718_3	.0160	857	.0096	721	.0063	870	.0030
718_4	.0180	864	.0057	721B	.0065	870B	.0033
718_4B	.0026	864B	.0066	722_2	.0025	870C	.0030
720B	.0172	865	.0578	722_2B	.0036	874	.0199
753	.0666	867	.0024	722_2C	.0038	876	.0161
753B	.0331	867B	.0022	782	.0121	897	.0144
790A	.0746	869BS	.0016	799	.1767	976	.0040
793	.0626	869CS	.0027	800B	.0015	976B	.0040
793B	.0492	876B	.0048	802	.0155	976C	.0048
798	.0920	905	.0024	802B	.0184	980	.0040
800	.0028	905B	.0024	802_2	.0069	980B	.0050
800C	.0010	973	.0174	802_2B	.0097	980C	.0084
807	.0058	973B	.0165	813	.0102	987	.0084
811	.0056	973C	.0245	813B	.0108	987B	.0182
811B	.0122	977	.0026	813C	.0102	987C	.0374
811C	.0150	977B	.0061	858	.1072	989	.0030
812	.0058	982	.0138	869	.0035	989B	.0037
812B	.0065	982B	.0148	869_2	.0160	989C	.0080
		982C	.0154				
		Average =	.0185				
						991	.0651
						991B	.0327
						991C	.0310
						992B	.0163
						993	.0062
						993B	.0085
						993C	.0081
						994	.0146
						994B	.0136
						Average =	.0166

Average I_r for all cubes = .0175.

Since it does not take into account certain systematic errors such as those which may occur in calibration of equipment and selection of samples, the apparent balance between average intensities for the two cases (north-seeking pole upward and north-seeking pole downward) is not to be taken too seriously. Figure 9 shows frequency distribution of remanent intensity, indicating that the greater number of values fall below the average.

With an average susceptibility of 0.00121 and a value of 0.567 cgs units for the earth's field, the magnetization resulting from induction is:

$$(0.567)(0.00121) = 0.00069 \text{ cgs units.}$$

Comparison of this value with the average remanent intensity of the granite gives:

$$(0.0175/0.00069) = 25.4$$

showing the remanent polarization to be approximately 25 times larger than the induced.

Arrows showing the direction and dip of the total remanent moment are plotted at appropriate station locations on the large-scale vertical intensity maps (Figs. 5, 6, and 7). The north-seeking pole is at the arrow tip, with the figure adjacent to the tip giving the dip above (if above, a plus sign is used) or below the horizon. Length of the arrows has no significance. Since true bed rock is not easily recognizable at all places, arrows on maps of outcrops 1 and 2 (Figs. 5 and 6) may, in several cases, represent directions and dips on boulders, therefore being in error

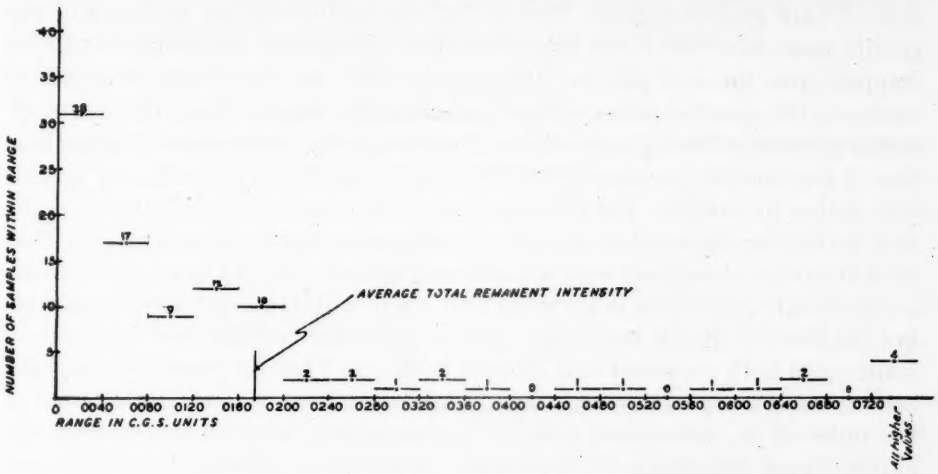

FIG. 9. Frequency distribution of total remanent intensity.

by the amount of movement to which the boulder has been subjected. Arrows on the map of outcrop 4 (Fig. 7) are all thought to represent data derived from true bed rock as this exposure has larger areas free from boulders than do the other two exposures.

IV. INTERPRETATION OF FIELD AND LABORATORY DATA

A. *Vertical Intensity Surveys*

By definition, an anomaly which attracts the north-seeking pole of the magnetometer is a high, while one repelling that pole is a low. This requires that the source of the high anomaly must be of south-seeking polarity, while that of the low anomaly must be of north-seeking polarity. Figures 5, 6, and 7 show that, with certain exceptions the vertical intensity high anomalies are associated with north-seeking arrows which are below the horizon, i.e., south-seeking poles are uppermost. Vertical intensity low anomalies are, therefore, associated with north-seeking poles which are uppermost. The earth's normal field would tend to induce

north-seeking poles below the horizon, pointing toward the earth's north magnetic pole, giving low magnetic relief upon the comparatively flat surfaces of bare granite. The relief would be due in part to the small topographic relief and in part to the minor changes in the average susceptibility of the granite. In contrast to this, the sharp magnetic relief and the apparent equality in relief between the high and low anomalies demonstrates the strong dominance of the remanent polarization over the induced polarization at a height of 3.3 feet (tripod height) above the bare granite.

In the northern part of the area, off the bare granite, Figure 1 shows a smooth high anomaly of several hundred gammas closure, centered around stations 525 and 526, covering an area large compared to that covered by any high mapped upon a bare granite surface. This is believed to indicate an approach of the granite mass to within a few hundred feet of the surface. Since highs and lows mapped upon the bare granite have approximately an equal number of closing contours, the question arises of how increasing the distance from the source affects a given set of strong anomalies arising principally from remanent magnetization. It is of interest to observe that the smooth high does not contain any notable lows within its outlines. The disappearance of the low anomalies found upon the bare granite requires explanation. Two possibilities suggest themselves: (1) That magnetizations developed with a north-seeking pole dipping below the horizon are systematically higher in intensity than those with the south-seeking pole below the horizon, giving an effective positive anomaly-creating field, high above, made up of both remanent and induced fields. (2) That the remanent magnetization, though apparently exceeding the induced magnetization by a factor of the order of 25, neutralizes itself at comparatively short distances from the source. Rapid diminution of the remanent field with an increase in distance from source could result from the equal strength and balanced number of its highs and lows. This would suggest that the induced magnetization is the only force effective at distances of a few hundred feet or more from the source.

From the evidence afforded by the vertical intensity maps of the shallow depth and the apparent balance in the relief and number of the positive and negative anomalies, the second possibility outlined above is preferred.

The vertical intensity maps suggest that the granite is composed of a series of blocks having north-seeking poles alternately pointing upward and downward. Horizontal dimensions of these blocks may be considered to approximate the anomaly limits, being roughly circular or elliptical in outline. Very roughly, they are thought to average 50 feet in diameter, though they vary from a minimum axis length of about 25 feet to a maximum axis length of 150 feet. These figures may represent maximum horizontal dimensions since a closer station pattern might break some anomalies into smaller ones.

2. *Vertical Gradient of the Vertical Intensity Survey*

A single pole may be used to represent a simple interpretation of results obtained here.

Let[16]

$$d = \frac{\Delta d}{\sqrt{\frac{\Delta Z_1}{\Delta Z_2}} - 1}$$

where ΔZ_1 and ΔZ_2 represent the anomalous fields in the lower and higher tripod positions respectively, Δd represents the vertical distance between lower and higher tripod positions, and d is the depth to what is called the equivalent pole.

To use the vertical gradient measurements in solving for an equivalent pole depth, the limits of each anomaly must be outlined arbitrarily since adjacent anomalies tend to obscure them. The ratio of $\Delta Z_1/\Delta Z_2$ is much less affected by errors in judgment as to anomaly limits than is either ΔZ alone.

TABLE III

VERTICAL GRADIENTS OF VERTICAL INTENSITY

No.	ΔZ_1	ΔZ_2	$\Delta Z_1 - \Delta Z_2$	Δd	d
		Magnetic Lows (gammas)			
753	−4,141	−2,195	−1,946	1.67 ft.	4.48 ft.
790A	−6,314	−3,705	−2,609	1.67 ft.	5.47 ft.
611	−7,617	−6,525	−1,292	1.67 ft.	17.58 ft.
865	−5,707	−5,449	−258	1.67 ft.	72.61 ft.
869	−6,358	−5,902	−456	1.67 ft.	43.95 ft.
976	−9,354	−6,900	−2,454	1.67 ft.	10.12 ft.
					Av. = 25.88 ft.
		Magnetic Highs (gammas)			
714	7,029	5,746	1,283	1.67 ft.	15.57 ft.
722	8,049	7,241	809	1.67 ft.	30.36 ft.
737	5,242	4,304	939	1.67 ft.	16.06 ft.
782	6,059	4,149	921	1.67 ft.	7.95 ft.
897	11,408	10,607	801	1.67 ft.	45.14 ft.
905	8,748	8,232	517	1.67 ft.	53.87 ft.
993	7,722	6,302	1,421	1.67 ft.	15.61 ft.
					Av. = 26.39 ft.

Average over both types of anomalies = 26.14 ft.
ΔZ_1 = Anomaly measured with tripod in low position
ΔZ_2 = Anomaly measured with tripod in high position
Δd = Change in tripod height
d = Depth to equivalent pole from average tripod position
Average relief over all anomalies from both high and low tripod positions = 6345 gammas.

Table III shows depths obtained over each of 14 anomalies. For negative anomalies, the average depth is 25.9 feet, while for the positive anomalies it is 26.4 feet, giving an average for all anomalies of 26.1 feet from the instrument at a height of 3.3 feet above the ground, or 22.8 feet below the ground surface.

The average depth from the ground surface of 22.8 feet may be taken as a radius for the magnetic unit blocks in the vertical dimension. The resultant diameter of 45.6 feet is of the same order of magnitude as the horizontal dimension

[16] C. A. Heiland, *Geophysical Exploration* (1940), pp. 382 and 407, Prentice Hall, Inc.

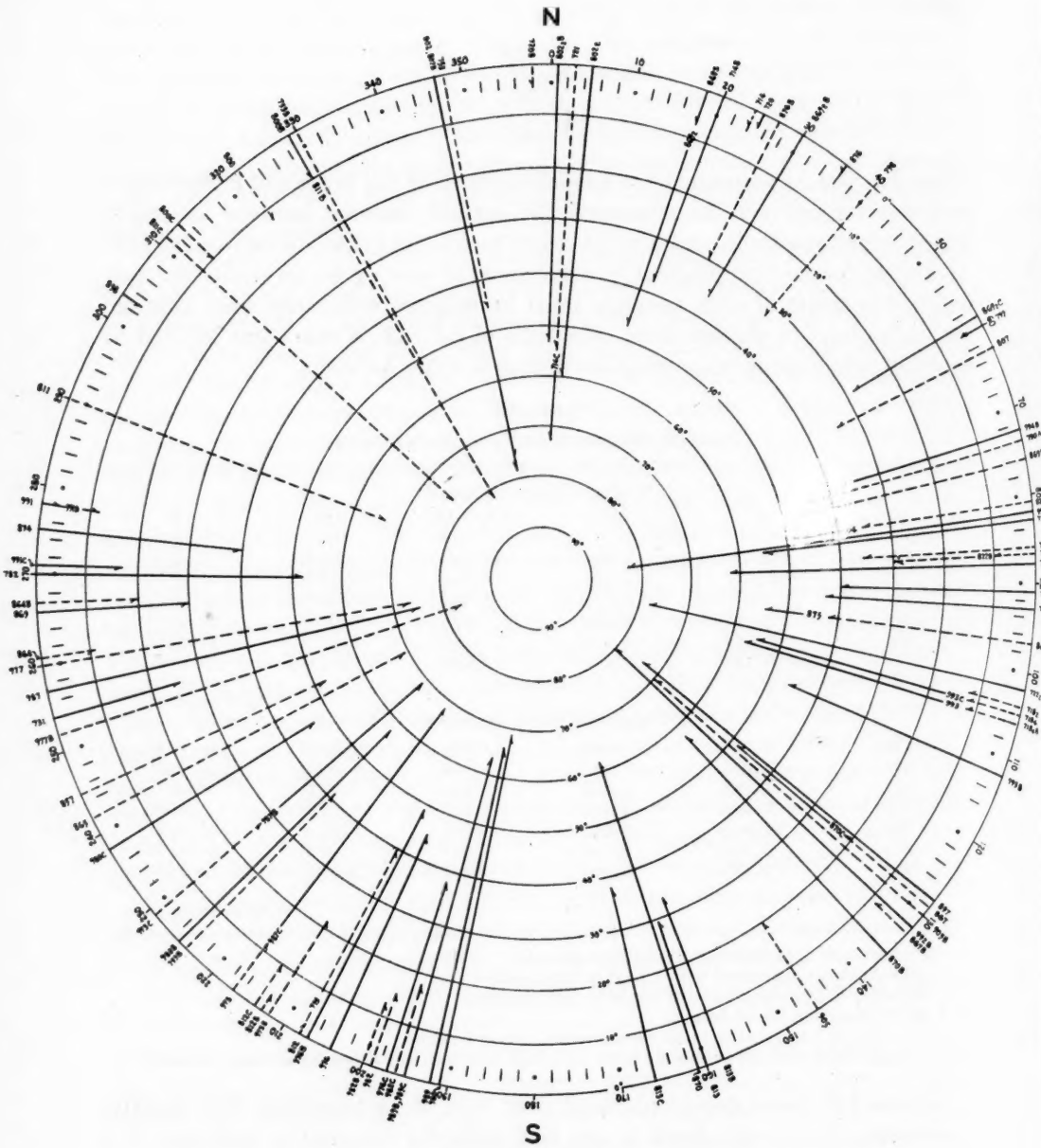
N
S
AZIMUTHS AND DIPS
NORTH SEEKING POLE OF REMANENT MAGNETIZATION FROM 97 CUBES CUT FROM 42 CORES.
DASHED LINES SHOW DIPS ABOVE, SOLID LINES BELOW THE HORIZON IN DEGREES.
Up
Down

FIG. 10. Azimuths and dips, north seeking pole of remanent magnetization.

of 50 feet taken from the maps (Figs. 5, 6, and 7). This suggests, but does not prove, that the blocks have vertical dimensions of about the same magnitude as their horizontal dimensions. The complexities of the problem are increased by lack of uniformity in the directions of magnetization.

Use of the formula for a magnetized line would yield a depth from the ground surface about one-half as large. Since this would assume a certain uniformity of direction in the magnetization, which does not appear to be the case (Fig. 10), assumption of a single pole is preferred.

The depths obtained for the single pole are to be considered a solution for a possible source distribution for the 14 principal anomalies mapped. This solution is not unique in that aggregates of poles at shallower depths could create the same gradients and fields. The single pole is thought to have no physical meaning, but to represent merely a rough mathematical equivalent to the much more complex volume magnetization which exists.

With the aid of certain assumptions, a solution for the remanent magnetization which creates the anomalies can also be made from these gradient measurements. This affords an interesting and independent check upon the average value of 0.0175 cgs units given in Table II.

If the average value for ΔZ (without regard to sign) is 6,345 gammas from Table III, and the average depths (d) of 26.1 feet (800 cm) (22.8 feet from the ground +3.3 feet to the average instrument position) from the surface be used in the formula:

$$M = (\Delta Z) \cdot (d^2),$$

the value of M (pole strength) is found to be about 40,000 cgs units. Heiland[17] gives the formula:

$$M = I_r S \quad \text{or} \quad I_r = \frac{M}{S}$$

for uniform magnetization where I_r is remanent magnetization and S is the "section" of the body. S is here used as the area over which the anomaly extends. Of course, the magnetization is not uniform but is treated as if it were in order to arrive at a rough approximation. If the radius of the average anomaly is taken as 800 cm (about 26 ft), then:

$$S = \pi(800)^2 = (2.0)(10^6) \text{ cm}^2 \text{ approximately.}$$

Substituting the values of S and M into the equation, a value of about 0.02 cgs units is found for I_r, which is to be compared to the mean value of 0.0176 cgs units found in Table III. This suggests that in reality the anomalies mapped could be considered to arise (for mathematical manipulation at least) from a surface magnetization.

[17] Heiland, op. cit., p. 382.

C. *Calculations on the Decrease of the Remanent Field with Increase in Distance from the Source*

As one purpose of the study is to investigate the field arising from remanent polarization, the values previously derived for the remanent intensity and the horizontal dimensions of the anomalies may be used as a basis for a calculation to indicate an order of magnitude for the rate of decrease of the remanent field.

Assuming a surface magnetization, one may use the formula $Z = WI_r$[18] where Z = vertical intensity, W = solid angle, and I_r = remanent polarization, to calculate vertical intensity effects at any height above the surface. If the surface be considered circular, the solid angle[19] at a point over its center is

$$W = 2\pi\left[1 - \frac{h}{(h^2 + r^2)^{1/2}}\right]$$

where h = height above surface, and r = radius of circular disk (25 feet).

Applying these two formulae to the case in which the magnetometer is 3.3 feet above the surface, a value for Z of about 9,600 gammas is obtained if I_r = 0.0175 cgs. This is a value similar to those measured.

Similarly, for a height of 50 feet above the surface, Z is about 1,200 gammas for a single disk and about 700 gammas for a combination of disks of opposite sign having 50 feet between their centers. In the latter case, the calculation is for a position directly over the center of one disk.

For a height of 500 feet, the corresponding values are 13 gammas for the single disk and 0 for the combination of disks.

This would seem to indicate (for the Spavinaw Granite) that the effects of the remanent magnetization will be sharply diminished at a height of 50 feet and eliminated at 500 feet. As the distance between anomalies increases, the height to which the remanent field would be effective would also increase.

D. *Total Intensity*

The values of relief and gradients on the air magnetic map at an average height of 675 feet above the ground (Fig. 2) are markedly lower than the vertical intensity values observed upon the bare granite (Figs. 5, 6, and 7), thus suggesting the elimination of the remanent field. The two profiles flown 1,175 feet above the ground show a further decrease in the relief of the anomalies of the order of 100 gammas (Fig. 3). This decrease in relief of about 100 gammas in 500 feet is to be contrasted with the decrease from 3.3 feet above the ground to about 675 feet. This latter decrease is of the order of 19,000 gammas. The extreme contrast is interpreted to confirm the elimination of the field arising from remanent polarization before the 675 foot level is reached. Continuation toward the source

[18] L. L. Nettleton, "Gravity and Magnetic Calculations," *Geophysics, Vol. VII*, No. 3 (1942), 293–310.

[19] A. J. F. Siegert, "A Mechanical Integrator for the Computation of Gravity Anomalies," *Geophysics, Vol. VII*, No. 4 (1942), 363.

from the map level would not be expected to bring out the effects of remanent magnetization.[20] It is of interest to note that it is possible to continue data obtained 3.3 feet above the granite upward an appropriate distance (a few hundred feet) to achieve the practical elimination of the field due to remanent magnetization. By continuing this data down again and subtracting it from the original values it is possible to show the effects of induced and remanent magnetization separately at the original level of mapping.

Evidence afforded by this map is not believed to support the dike[21] theory of origin for the Spavinaw Granite because the anomaly does not have a shape which is sufficiently elongated in any one direction. The magnetic data are consistent with the possibility of intrusion of a stock-like body, however.

A rough calculation shows that even if the structural relief over the granite in the Spavinaw anticline be taken as 200 feet instead of the 90 feet measured on the top of the Arbuckle only a small fraction of the magnetic relief associated with the granite outcrops can reasonably be assigned to this cause. Consequently a large part of the anomaly present can be most reasonably explained as due to a polarization change in the basement. Such a change would normally accompany a petrologic change and may therefore be considered good evidence of an intrusion of one rock type into another. No evidence as to the date of the intrusion is available from the magnetic anomaly, however.

E. *Remanent Magnetization and Susceptibility*

As shown in Figure 9 the frequency distribution of remanent intensity has a peak well below the average value, at a point relatively close to zero. Deviation from a probability curve may be considered evidence of a low degree of uniformity in the magnetic orientation of the magnetic grains or it might indicate that the cubes used in the measurements are too small to contain a representative number of grains. Where the former case is true the ratio between the average intensity and the most frequent intensity may be an index to the uniformity of orientation of the magnetite grains in a rock, the orientation being perfect where the average and most frequent values are equal and very poor where the average value deviates greatly from the most frequent. It seems that the magnetite content might be less important than the uniformity of orientation in determining the remanent intensity of a rock.

Figure 10, previously referred to, shows a plot of azimuth and dip of all remanent magnetizations, where zero degrees in azimuth is geographic north. A weak concentration may exist between azimuths 80°–100° and 260°–280° though this is not clear. Dips appear to have an even weaker concentration, if any.

Three apparent discrepancies between remanent field dip and the sign of the vertical intensity anomaly have been tentatively explained. Figure 5 shows a

[20] L. J. Peters, "The Direct Approach to Magnetic Interpretation and its Practical Application," *Geophysics, Vol., XIV*, No. 3 (1949), 80.

[21] Carl Tolman, and K. K. Landes, op. cit., 80.

strong magnetic low centered on station 869. This requires the north-seeking pole to be above the horizon, whereas for cube numbers 869, 869_2, 869_2B, 869_2C, and 869S an average dip of the north-seeking pole 21 degrees below the horizon and all individual dips below the horizon. Cubes 869BS and 869CS show the north-seeking pole an average of 43 degrees above the horizon and dips of both are above the horizon. These cubes are below 869S, which exhibits only a 7 degree downward dip.

Figure 6 shows a magnetic low over station 802, while cubes 802, 802B, 802_2, and 802_2B have an average dip 66 degrees below the horizon and that all individual dips are below the horizon, though there is a regular decrease in the amount of downward dip as the cubes come from deeper position.

Figure 7 shows a magnetic low over station 976. There is a downward dip for cubes 967, 976B, and 976C, the average dip being -44 degrees.

It is possible that a boulder which had rotated on a horizontal axis has been cored at station 869, but this is not considered probable. The chances of a boulder having been cored at either station 802 or 976 are believed to be very small. The preferred explanation is that, at a shallow depth (a few inches probably) beneath stations 802 and 976, a reversal of dip would be found just as it has been found in cubes 869BS and 869CS at station 869. This suggests that only a thin remnant of a block in which the dip was downward now remains at these locations, the remainder of the block having been removed by erosion. The magnetometer readings are dominated by the underlying block, giving negative anomalies in each case.

V. SUMMARY AND CONCLUSIONS

A. *Decrease of Remanent Field with Increase in Distance from the Source for the Spavinaw Granite*

Evidence on the decreasing importance of remanent magnetization with increase in distance from the source in the particular igneous body studied may be summarized as follows:

1. On the ground, the vertical intensity maps show a series of strong positive and negative anomalies. On each of the maps, the positive and negative anomalies are approximately equal in number, areal extent, relief, and gradients. The relief of the anomalies is so great that an extreme and very unlikely susceptibility contrast (of the order of 0.0400 cgs units compared to the measured value of about 0.001) would have to be assumed to account for it on the basis of induced magnetism only. From these maps alone (unsupported by any other evidence), it would be logical to assume that remanent magnetism is dominant in the field mapped at a level of 3.3 feet above the bare granite.

2. The total intensity map at an average height of 675 feet above ground, and the two total intensity profiles at 1,175 feet above ground, show horizontal gradients, relief, and vertical gradients markedly smaller than those observed in vertical intensity 3.3 feet above the ground. This indicates the complete lack of remanent polarization effects in the total intensity data.

3. Measurements of remanent intensity and volume susceptibility suggest that the induced polarization is lower than the remanent polarization by a factor of approximately 25, in agreement with evidence from the field maps. Comparison of average values for remanent magnetization intensities for cubes with dips above the horizon and below the horizon suggests a cancellation of remanent intensity lows by remanent intensity highs at short distances from the sources.

4. Calculations of the maximum effect of two disks of opposite sign having polarizations of the order measured show that only about 1,400 gammas (+700 above a positive disk and −700 above a negative disk) relief would be found at 50 feet from the two sources compared to the maximum of 20,000 gammas measured 3.3 feet above the granite. The carrying power of the remanent magnetization is dependent partly upon the width of separation of anomalies of opposite sign and partly upon the pole strengths involved.

The evidence, in its entirety, from both field and laboratory studies indicates the elimination of any effects from remanent intensity for this particular igneous body at heights of not more than a few hundred feet.

B. *Origin of the Pattern of Remanent Magnetization Exhibited by Igneous Bodies*

Bruckshaw and Robertson[22] have suggested that convection currents in the magma during cooling may be responsible for the pattern of remanent magnetization exhibited by certain dikes studied by them. When applied to the Spavinaw Granite, this idea leaves to be explained the suspected periodic reversal of dip of the north-seeking pole with increase in depth, as well as the manner in which the currents select poles of like sign, to be pointed upward or downward. It cannot be said, however, that evidence now available conclusively condemns the idea.

The possibility of the existence of fairly large electric currents in a cooling magma, with consequent magnetic fields, is very speculative but worthy of consideration. This would appear to require the creation of fields larger than that of the earth to orient grains against the earth's field. To create a magnetic field of 0.6 gauss at a distance of 25 feet, an infinitely long straight conductor carrying approximately 2,300 amperes would be required. For the creation of this field at the center of a plane coil, only 728 amperes would be required. The possible existence of currents of this general order of magnitude is uncertain. Also, additional sampling is needed to afford a more complete pattern for study.

C. *The General Role of Remanent Magnetism in Creation of Magnetic Anomalies*

A general review of magnetic maps over relatively large areas shows that the great number of anomalies in areas with one thousand feet or more of sediments have relief of five hundred gammas or less, but that there are exceptions such as the huge low in Parmer County, West Texas, the highs at Crosbyton[23] in West

[22] J. McG. Bruckshaw, and E. I. Robertson, op. cit.

[23] E. W. McLemore, Paul Weaver, and D. C. Barton, "The Crosbyton Anomaly, Southeastern Crosby Co., Texas," *Geophysics, Vol. VII*, No. 2 (1942), 179–191.

Texas and Rison in Arkansas, where remanent polarization may easily play a significant part. In terms of relief or character of anomalies, it does not appear readily possible to make a sharp demarcation above which anomalies are apt to be partly or wholly due to remanent polarization.

It seems reasonable to assume that the spacing found between remanent anomaly centers and the volumes of rock involved in creation of the anomalies, i.e., volumes in which the north-seeking arrows are dominantly in one direction, may vary tremendously in nature with a consequent large variation in the vertical distance through which the effects of remanent magnetization may be felt. The Rison, Arkansas, anomaly of the order of 20,000 gammas, which apparently carries through about two thousand feet of sediments, may well be an example of a high remanent magnetization distributed uniformly through a periodotite plug, combined with a high induced field,

Discovery of relations between the ordinarily described physical or chemical characteristics of permanently magnetized igneous and metamorphic rocks and the effectiveness of the remanent field at various distances will make an interesting study for the future. Magnetic ores would seem to be of particular economic interest in this connection since the question of whether an ore body may be found by magnetic methods under a given thickness of cover, or at a given height above the terrain if air surveying is used, may depend upon the effectiveness of the combination of remanent and induced polarization.

VI. ACKNOWLEDGMENTS

The Stanolind Oil and Gas Company permitted use of their field and laboratory equipment at all times during the course of this investigation. The Frost Geophysical Company[24] and the Aero Exploration Company gave air photos and furnished the air magnetometer and airplane required in making the air magnetic map. These companies also gave freely of the time of their personnel in making the necessary photo mosaic and plotting and contouring the air magnetic data.

The Harvard University Department of Geology bore a portion of the cost of the air magnetic work.

Many individuals gave sound advice on various phases of the project. Duane Reno aided greatly in suggesting methods for overcoming certain laboratory and field problems. Dr. R. C. Coffin offered encouragement and criticism at various stages of the work. Dr. Joseph A. Sharpe made many helpful comments on preparation of the air magnetic data and organization of the paper in general. Dr. Arnold Siegert assisted by commenting upon various theoretical aspects of the problem. V. L. Jones offered field and laboratory assistance on certain parts of the problem. Dr. R. M. Dreyer read and suggested changes in the manuscript. The Faculty of the Harvard University Department of Geology, particularly Dr. Francis Birch, critically read much of the paper, suggesting many revisions. Anne

[24] Now the Frost Airborne Survey Corp.

Mellin Hawes patiently typed the original manuscript and aided in criticizing the composition.

The assistance of these organizations and individuals is greatly appreciated.

APPENDIX

A. *Relation of Magnetite Volume Proportion to Effective Susceptibility*

Nettleton and Elkins,[25] using a small number of measurements on rock samples plus certain theoretical considerations, have arrived at a formula relating (in rocks of the type under consideration) the true rock susceptibility, S_3, the volume percentage (or proportion which is the percentage divided by 100) of magnetite, P_1, and a factor called effective susceptibility, k'. The relationship is $S_3 = P_1 k'$.

The volume percentage of magnetite was determined for nine samples of Spavinaw Granite. The sample, crushed to pass a one-hundred mesh screen, was poured through a drinking straw held against the pole of an alnico magnet creating about 2,240 gauss maximum field strength. The magnetic material was held in the straw opposite the pole while the non-magnetic material passed through. The volume percentages were calculated from measured densities of the magnetic material with assumed densities of 5.17 for magnetite and 2.63 for the non-magnetic portion of the samples. The susceptibilities of the non-magnetic material which passed through the straw varied from 0.00018 to 0.0061 in cgs units per cc.

TABLE IV

RELATION OF MAGNETITE VOLUME PROPORTION TO EFFECTIVE SUSCEPTIBILITY

S_1 = Susceptibility per unit volume of the granite as taken from the field in cgs units
S_2 = Susceptibility per unit volume of the non-magnetic portion of the sample in cgs units
S_3 = Difference between S_1 and S_2
D = Density of the magnetic concentrate
R = Volume percentage of magnetite in the magnetic concentrate
$k' = S_3 \times 100 / P_1$ = Effective susceptibility factor
P_1 = Volume percentage of magnetite removed in the separation
P = Total volume percentage of magnetite obtained by multiplying P_1 by S_1/S_3

No.	S_1	S_2	S_3	D	R	S_1/S_3	P_1	P	$k' = \frac{S_3 \times 100}{P_1}$
718_4	.00126	.00038	.00088	4.314	66.33	1.421	1.884	2.68	.047
753	.00108	.00031	.00077	3.958	52.27	1.396	1.240	1.73	.062
800	.00107	.00018	.00089	4.461	72.15	1.197	1.710	2.05	.052
865	.00155	.00041	.00114	4.097	57.64	1.395	0.817	1.11	.139
867	.00155	.00029	.00126	4.056	56.18	1.224	1.363	1.69	.093
869	.00119	.00023	.00096	4.026	54.93	1.233	1.366	1.68	.070
897	.00120	.00040	.00080	4.124	58.84	1.494	1.386	2.07	.058
987	.00115	.00031	.00084	4.045	55.74	1.370	1.134	1.55	.074
992	.00115	.00062	.00053	4.067	56.60	2.154	.0659	1.42	.081
									Av. = .076

[25] L. L. Nettleton, and T. A. Elkins, "Association of Magnetic and Density Contrasts with Igneous Rock Classification," *Geophysics, Vol. IX*, No. 1 (1944), 60–75.

The magnetite content of the nine samples in per cent by volume varied from 1.11 to 2.68, the average being 1.78. The original susceptibilities for the same specimens varied from 0.00154 to 0.00107 in cgs units per cc, averaging 0.00124.

With the formula quoted above, $k' = S_3/P_1$, the average value for k' is 0.00076 (volume percentage) or 0.076 (volume proportion as used by Nettleton and Elkins). This is lower than the best value of 0.25, stated in the above mentioned paper, by a factor of 3.3.

For each sample the difference between the original susceptibility and the susceptibility of the non-magnetic portion is the value corresponding to the volume percentage of magnetite extracted from it. This volume percentage of magnetite extracted must then be multiplied by the ratio of the original susceptibility to the difference in susceptibility to find the total volume percentage of magnetite present in the sample. Results for the nine samples are show in Table IV.

It is evident that an important portion of the effectively susceptible minerals of mineral (presumably magnetite) is not recovered in the magnetic separation since the susceptibility of the non-magnetic portion may be as high as one-third that of the original susceptibility. Microscopic examination shows that some magnetite occurs as inclusions (in hornblende and other minerals) which are too small to become separated in a sample crushed to 0.01 inch.

If the density of 2.63 assumed for the minerals other than magnetite in the magnetic concentrate is approximately correct, an average of about 41 percent by volume of the magnetic concentrate is not magnetite. It is probably true that some quartz and feldspar containing no magnetite inclusions are unavoidably present in the concentrate, but a large part of the 41 percent by volume is probably present due to magnetite inclusions. The possibility arises that the demagnetization factor for the magnetite contained in the inclusions is not the same as that for the larger grains. Other possibilities may also suggest themselves with further work.

B. *Derivation of Formula for Total Moment*

The component moment A in the XY plane, shown in Figure 4, may be divided into two components: one parallel to the X direction and one parallel to the Y direction, called M_x and M_y respectively. Then:

$$A^2 = M_x^2 + M_y^2.$$

Similarly:

$$B^2 = M_y^2 + M_z^2$$

and:

$$C^2 = M_z^2 + M_x^2.$$

The square of total moment, M, will be equal to the sum of the squares of the

components parallel to the three mutually perpendicular axes, i.e., X, Y, and Z axes. Thus:

$$M^2 = M_x^2 + M_y^2 + M_z^2.$$

However, since the values of M_x, M_y, and M_y are not measured, their relation to A, B, and C, which values are measured, is of interest. It is evident that:

$$A^2 + B^2 + C^2 = 2(M_x^2 + M_y^2 + M_z^2) = 2M^2.$$

Therefore

$$M = \sqrt{\frac{A^2 + B^2 + C^2}{2}}.$$

QUALITY OF GEOPHYSICAL MEASUREMENTS*

E. V. McCOLLUM†

ABSTRACT

The quality of geophysical measurements may be obtained from statistical studies in which the probable error of a single observation is estimated. Since many geophysical functions, when plotted in profile form, resemble smooth mathematical curves upon which "static" caused by random errors is superimposed, it is possible to substantially remove the measured function from the errors through the construction of difference tables. Higher orders of differences consist primarily of systematic combinations of individual errors. When a function, u, is observed at equally spaced points, the probable error of a single observation may be obtained from the equation

$$\epsilon \leqq \frac{0.8453}{(\sum K^2)^{1/2}} \cdot \frac{\sum |\Delta^m u|}{n}$$

where u is the measured function,
m is the order of the differences,
n is the number of measurements, and the
K's are the binomial coefficients of the order, m.

Application of the method to seismic and gravity profiles results in probable errors that are consistent with those obtained from the studies of basic data acquired in the field. The method may also be used in many other measurements in the field and laboratory.

The quality of geophysical measurements may be obtained in terms of probable error calculations. Such determinations aid an operator in deciding which anomalies may be real; furthermore, they furnish a means of judging the effectiveness of the crew that is making the survey. In routine geophysical surveys, where all the original notes on the field measurements are available, it is possible to predict the probable error in the reduced values, such as Bouguer Gravity or Seismograph Datums, which are placed on a map and contoured. In other instances, only maps or cross-sections are available that show the reduced or corrected quantities. It is with this type of data that this paper is primarily concerned.

In several types of geophysical surveys it is customary to make observations along straight lines at approximately equally spaced points, the spacing being dependent upon the amount of detail desired. Many geophysical functions, when plotted in profiles, resemble smooth mathematical curves upon which "static" caused by random errors is superimposed. It is the purpose of this paper to describe a method whereby reduced geophysical quantities and the random errors of measurement may be substantially separated from each other and, finally, a value obtained for the probable error.

* Presented before the Geophysical Society of Tulsa May 10, 1951, before the Eastern Regional Meeting October 12, 1951, and before the Joint Regional Exploration Meeting at Dallas, November 19, 1951. Manuscript received by the editor June 14, 1951.

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TABLE 1

DIFFERENCE TABLE FOR THE FUNCTION $y=x^2$, ILLUSTRATING THE EFFECT OF AN ERROR OF 0.1 IN y AT $x=5$

x	$y=x^2$	Δy	$\Delta^2 y$	$\Delta^3 y$	$\Delta^4 y$
0	0				
		1			
1	1		2		
		3		0	
2	4		2		0
		5		0	
3	9		2		+0.1
		7		+0.1	
4	16		2.1		−0.4
		9.1		−0.3	
5	25.1		1.8		+0.6
		10.9		+0.3	
6	36		2.1		−0.4
		13		−0.1	
7	49		2		+0.1
		15		0	
8	64		2		0
		17		0	
9	81		2		
		19			
10	100				

THE METHOD

The tools used in making the probable error calculations are:

1. Difference Tables, and
2. A few simple Error Formulae which may be found in most elementary text books on errors, and many handbooks of the applied sciences.

Table 1 is a Diagonal Difference Table for the parabola $y=x^2$, patterned after Scarborough.[1] An error of 0.1 has been injected into y at $x=5$.

It will be noted that the function $y=x^2$ has disappeared in the third and higher order of differences. In general, the $(n+1)$th differences of a polynomial of the nth order are zero.[2] If a measured function may be closely approximated by a polynomial in the vicinity of each point under consideration, then the construction of a difference table substantially removes the function and leaves the errors —it is upon this premise that the method under discussion is based.

Another result is that the error increases with the successive differences. A study of the various difference columns discloses that the coefficients of the error are the binomial coefficients with alternating signs. If only one error were present it could easily be located and evaluated; however, such simplicity is never attained in practice. Table 2 is a Diagonal Difference Table in which it is assumed that the observed function consists solely of errors. This table shows clearly the manner in which the errors combine, i.e., the coefficients of the errors are the bi-

[1] J. B. Scarborough, *Numerical Mathematical Analysis*, The Johns Hopkins Press (1930), p. 43.

[2] Whittaker and Robinson, *The Calculus of Observations*, 4th Edition, Blackie & Son, Ltd. (1944), p. 6.

TABLE 2

DIFFERENCE TABLE FOR FUNCTION WHICH CONSISTS SOLELY OF RANDOM ERRORS

x	E	ΔE	$\Delta^2 E$	$\Delta^3 E$
0	E_0			
		E_1-E_0		
1	E_1		$E_2-2E_1+E_0$	
		E_2-E_1		$E_3-3E_2+3E_1-E_0$
2	E_2		$E_3-2E_2+E_1$	
		E_3-E_2		$E_4-3E_3+3E_2-E_1$
3	E_3		$E_4-2E_3+E_2$	
		E_4-E_3		
4	E_4			

nomial coefficients, and the same set of coefficients persists throughout each column of the difference table.

The standard formula[3] for the calculation of the probable error, ϵ, of a single observation is

$$\epsilon = 0.6745[\sum \rho^2/(n-1)]^{1/2} \tag{1}$$

where the ρ's are the residuals and n the number of measurements.

Peter's Formula[3] for the probable error is

$$\epsilon = 0.8453 \sum \rho/[n(n-1)]^{1/2} \tag{2}$$

where the sum of the residuals is taken without regard to sign.

When n is large, Peter's Formula[3] may be written as

$$\epsilon = 0.8453 \sum \rho/n \tag{3}$$

which states that the probable error of a single observation is approximately 0.85 times the average value of the residuals taken without regard to sign.

It is seldom possible in physical measurements to directly measure the quantity sought. For example, in gravity measurements it is necessary to not only measure gravity but determinations of elevation and latitude must also be made before Bouguer Gravity can be calculated. A similar situation exists in seismograph surveys in that elevations and near surface corrections are usually obtained before subsea datums can be computed. When several functions are measured, the probable error in the end product sought may be predicted by the application of some form of the Law of Progression of Errors. If Q is a linear function of $q_1, q_2, q_2, \cdots$, such as

$$Q = K_1q_1 + K_2q_2 + K_3q_3 + \cdots \tag{4}$$

in which the probable errors $\epsilon_1, \epsilon_2, \epsilon_3, \cdots$ occur in $q_1, q_2, q_3, \cdots$ the probable error, ϵ, in Q is given by[4]

[3] Leroy D. Weld, *Theory of Errors and Least Squares*, Macmillan (1922), p. 154.

[4] Weld, op. cit., p. 190.

$$\epsilon = (K_1^2\epsilon_1^2 + K_2^2\epsilon_2^2 + K_3^2\epsilon_3^2 + \cdots)^{1/2} \tag{5}$$

when $K_1 = K_2 = K_3 = \cdots = 1$, Equation (5) becomes

$$\epsilon = (\epsilon_1^2 + \epsilon_2^2 + \epsilon_3^2 + \cdots)^{1/2}. \tag{6}$$

Equation (6) gives the Law of Propagation of Errors in a form that is frequently seen in practice.

Another form of the Law of Propagation of Errors may be derived as follows: suppose that each q is subject to the same probable error, ϵ_1, such that $\epsilon_1 = \epsilon_2 = \epsilon_3 = \cdots = \epsilon_1$, then Equation (5) becomes,

$$\epsilon = \epsilon_1(K_1^2 + K_2^2 + K_3^2 + \cdots)^{1/2} = \epsilon_1(\sum K^2)^{1/2}. \tag{7}$$

Application of Equation (7) to Table 2 gives,

$$\epsilon = \epsilon_1 \quad \text{for} \quad E, \qquad \epsilon = \epsilon_1(1^2 + 1^2)^{1/2} = (2)^{1/2}\cdot\epsilon_1 \quad \text{for} \quad \Delta E,$$

$$\epsilon = \epsilon_1(1^2 + 2^2 + 1^2) = (6)^{1/2}\cdot\epsilon_1 \quad \text{for} \quad \Delta^2 E,$$

$$\epsilon = \epsilon_1(1^2 + 3^2 + 3^2 + 1^2)^{1/2} = (20)^{1/2}\cdot\epsilon_1 \quad \text{for} \quad \Delta^3 E, \quad \text{etc.}$$

Absolute values of each column in Table 2 may be averaged. Then, applying Equation (3) gives

$$\epsilon = 0.8453 \sum \Delta^m E/n \tag{8}$$

where m is the order of the differences being considered and n is the number of the differences. Eliminating ϵ between Equations (7) and (8) gives,

$$\epsilon_1 = 0.8453 \sum \Delta^m E/n(\sum K^2)^{1/2}. \tag{9}$$

Equation (9) holds to a very good approximation when the observations are all errors. This will be demonstrated in the next section. In general, if a function u is being analyzed, the difference table will not completely eliminate u and Equation (9) should be modified by writing it as an inequality; also, the subscript of ϵ_1 should be dropped. Then,

$$\epsilon \leqq \frac{0.8453}{(\sum K^2)^{1/2}} \cdot \frac{\sum \Delta^m u}{n}. \tag{10}$$

AN EXPERIMENT WITH RANDOM ERRORS

In order to test Equation (10) the Probability Curve for the probable error $\epsilon = 0.3$ was constructed. The equation for this curve is[5]

$$y = \frac{h\Delta}{\sqrt{\pi}} \cdot e^{-h^2x^2} \tag{11}$$

where y is the probability,
h is the precision index,

[5] Weld, op. cit., p. 144.

$\Delta = 0.1$, is the scale interval,
x is the error, and
e is the base of natural logarithms.

The probable error, ϵ, and the precision index h are related according to the formula[6]

$$h\epsilon = 0.4767. \tag{12}$$

For the constants as given, Equation (11) becomes

$$y = 0.08969e^{-2.527x^2}. \tag{13}$$

Equation (13) is shown in curve form in Figure 1. One hundred errors were selected to conform to the probability curve shown, in which 9 had zero error,

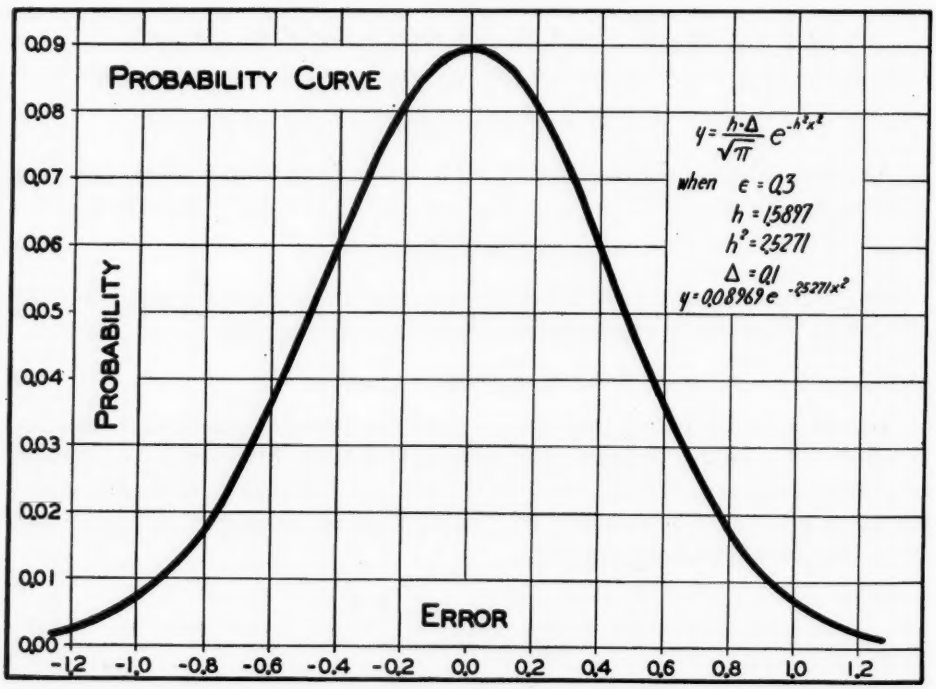

FIG. 1. The probability curve for a probable error of 0.3 and a scale interval of 0.1.

9 had an error of -0.1, 8 had an error of $+0.1$, etc., until, finally, 1 error of 1.1 and 1 error of -1.1 were selected. The 100 values so selected were written on separate slips of paper and thoroughly mixed in a box, after which they were drawn at random and numbered 1, 2, 3, etc., up to 100. The order in which the errors were drawn is shown in Curve C_4 of Figure 2.

In order to test Equation (10) a difference table was constructed of the 100

[6] Weld, op. cit., p. 154.

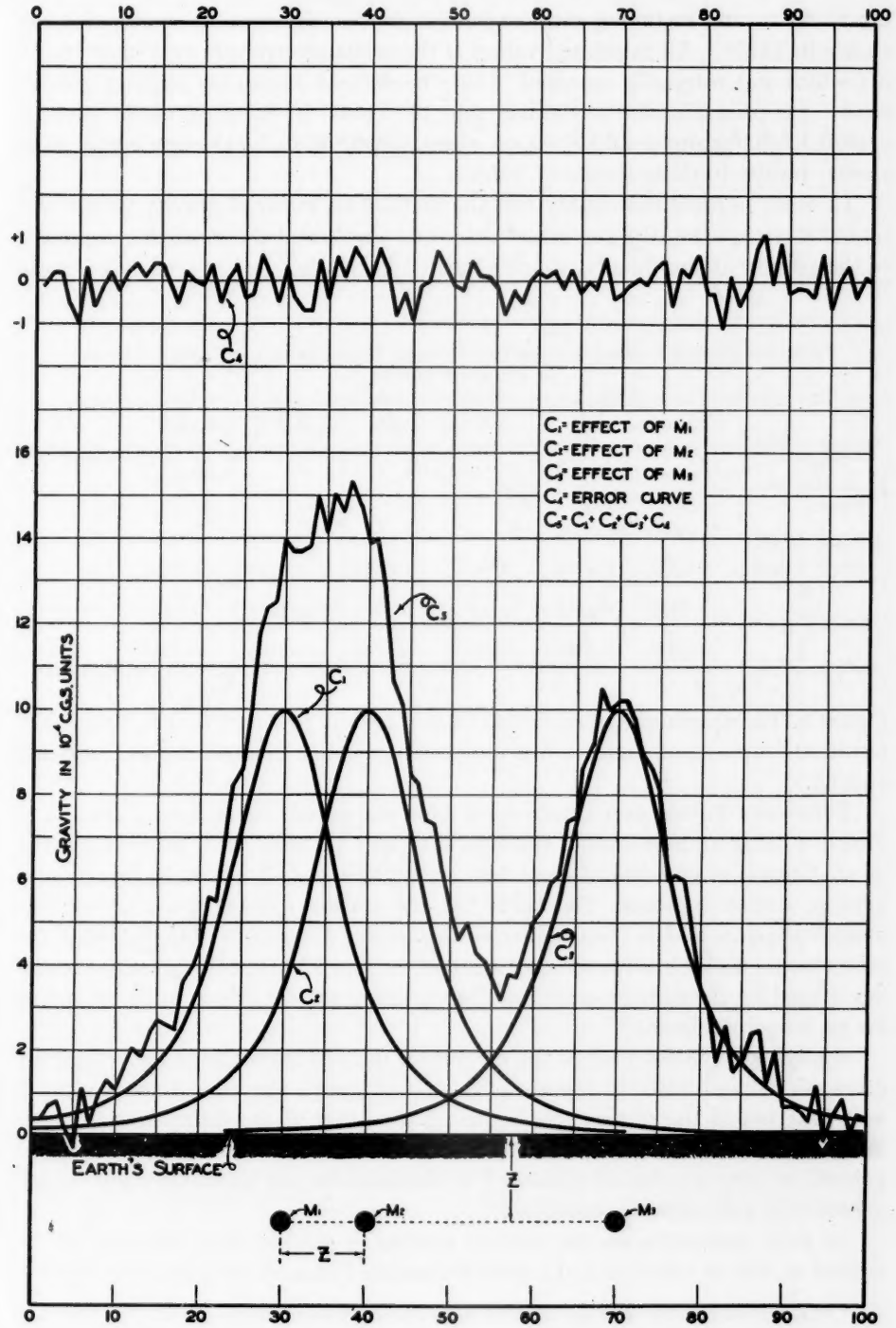

FIG. 2. One hundred random errors plotted in profile form, the vertical component of gravity for three spheres spaced as shown, and a composite gravity curve.

errors up to and including sixth order differences. The results of this test are shown in Table 3. All calculated values of the probable error are very close to the 0.3 which was originally assumed. That the derived values are slightly greater than 0.3 is primarily due to the fact that the "tails" of the error curve were included in the errors ± 1.1. Tests on other distributions of the 100 errors gave similar results to those shown in Table 3.

In order to more thoroughly test the method an artificial gravity profile was manufactured, using the 100 errors described above and the vertical component of the gravity attraction of 3 spheres burried at depth Z and spaced as shown in

TABLE 3

PROBABLE ERRORS COMPUTED FROM DIFFERENCES TAKEN FROM 100 RANDOM ERRORS. (CURVE C_4 OF FIGURE 2)

	E	ΔE	$\Delta^2 E$	$\Delta^3 E$	$\Delta^4 E$	$\Delta^5 E$	$\Delta^6 E$
m	0	1	2	3	4	5	6
$\sum$ of Absolute Values	35.8	51.4	87.8	160.1	294.9	551.3	1058.2
n	100	99	98	97	96	95	94
Average of Absolute Values	0.3580	0.5192	0.8959	1.6505	3.0719	5.8032	11.2574
$\frac{0.8453}{\sqrt{\sum K^2}}$	0.8453	0.5978	0.3452	0.1890	0.1010	0.05325	0.02781
ϵ	0.3026	0.3104	0.3093	0.3119	0.3103	0.3090	0.3131

Figure 2. The maximum attraction of each sphere is 10×10^{-4} C.G.S. Units. The resultant Curve C_5 of Figure 2 was plotted from points computed with a spacing of $0.1Z$.

Difference Tables were constructed from the values taken from Curve C_5 of Figure 2 using various station spacings such as $0.1Z$, $0.2Z$, etc., up to a spacing of $2Z$. Several second difference profiles are plotted in profile form in Figure 3 for various station spacings. The curve for the station spacing $w = 0.1Z$ consists mostly of errors and is very similar to the second differences obtained from the errors alone. As the station spacing is increased, the effects of the gravity anomalies caused by the spheres contribute increasingly greater effects until the errors are no longer dominant.*

Applying Equation (10) to the differences derived from Curve C_5 of Figure 2 gives the values plotted in Figures 4 and 5. In Figure 4 Probable Error is plotted as a function of the station spacing using the order of the differences as a parameter. It will be noted that when the left hand ends of these curves are extrapolated to zero a value of about 0.3 is obtained for the probable error, which agrees with the original assumption.

In field measurements the station spacing is usually fixed and cannot be altered at will in order to make error estimates. For such data another curve is

* At still greater station spacings the effect of the anomalies may possibly decrease, but the study of large station spacings is not within the scope of this paper.

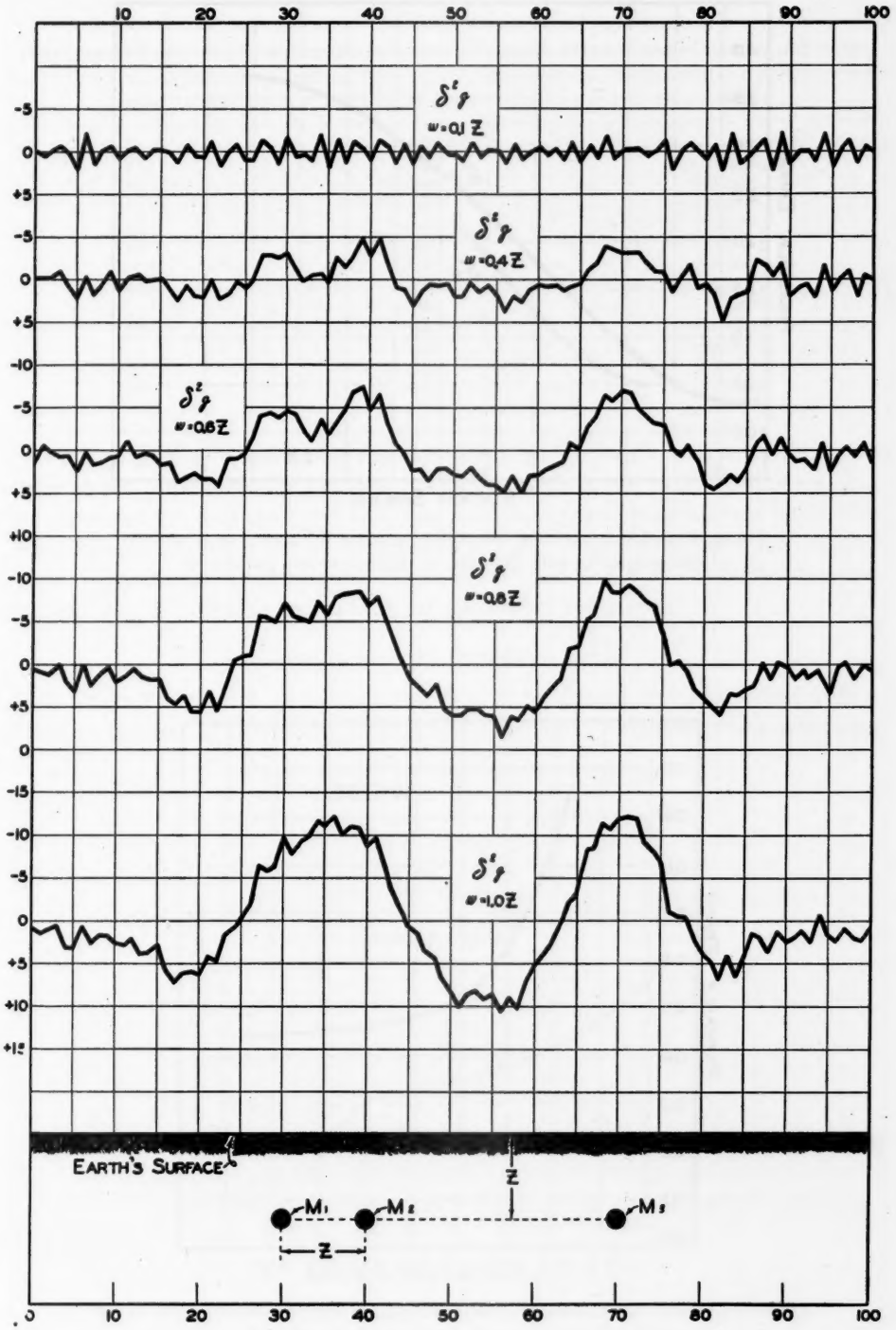

FIG. 3. Second differences in profile form taken from Composite Curve C_5 of Figure 2, with station spacing being the parameter.

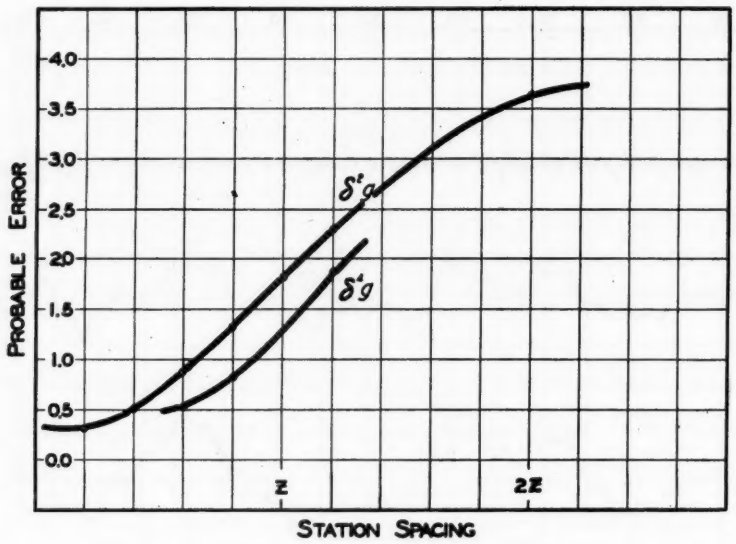

FIG. 4. Probable errors from composite curve C_5 of Figure 2 as a function of station spacing with the order of differences as a parameter.

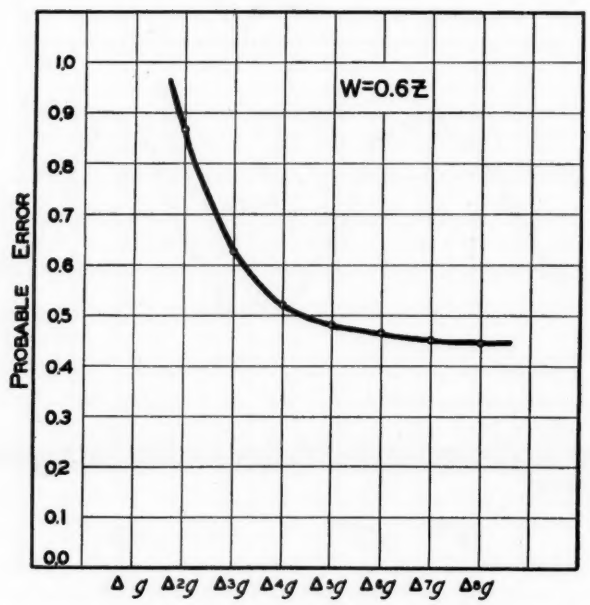

FIG. 5. Probable errors from composite curve C_5 of Figure 2 as a function of the order of difference with a station spacing of 0.6 z.

TABLE 4

DIFFERENCE TABLE FOR SEISMOGRAPH PROFILE IN GUTHRIE FIELD, LOGAN COUNTY, OKLAHOMA

Station	t	$\delta^2 t$
89	1.021 sec.	
88	1.025	−0.030 sec.
87	0.999	+0.024
69	0.997	+0.001
71	0.996	+0.002
72	0.997	−0.011
73A	0.987	+0.005
74	0.982	+0.007
75	0.984	−0.006
76	0.980	+0.009
153	0.985	−0.010
152	0.980	+0.002
151	0.977	

shown in Figure 5 in which the calculated Probable Error is plotted against the order of the differences for a constant station spacing, $w=0.6Z$. It appears that the right hand end of the curve is asymptotically approaching a lower limit. The value for the eighth order of differences is 0.44, which is higher than the 0.3 originally assumed. It is believed that this method will give conservative error values, that is, probable errors that are somewhat too large.

APPLICATION TO OBSERVED DATA

In order to test the method against field data, Profile *H* was selected from a Bouguer Gravity Map of the Garber, Oklahoma Area. This profile is 8 miles long

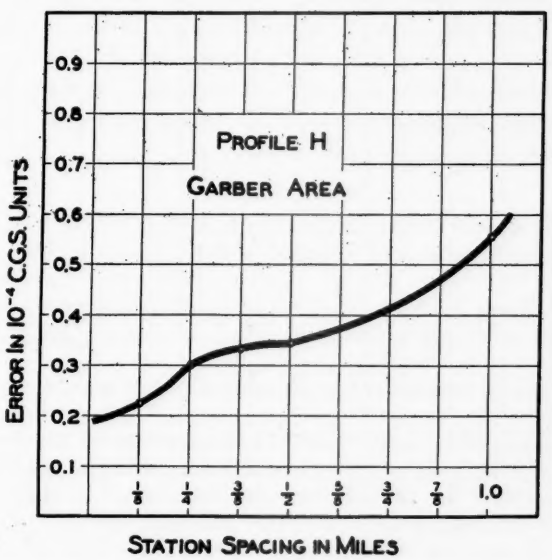

FIG. 6. Probable error computed from second differences as a function of station spacing for a Bouguer gravity profile at Garber, Oklahoma.

TABLE 5
DIFFERENCE TABLE FOR GEOCHEMICAL PROFILE, JONES COUNTY, TEXAS

u	Δu	$\Delta^2 u$	$\Delta^3 u$	$\Delta^4 u$
21				
	21			
42		−49		
	−28		66	
14		17		−73
	−11		−7	
3		10		−4
	−1		−11	
2		−1		42
	−2		31	
0		30		−109
	28		−78	
28		−48		160
	−20		82	
8		34		−119
	14		−37	
22		−3		11
	11		−26	
33		−29		71
	−18		45	
15		16		−36
	−2		9	
13		25		−63
	23		−54	
36		−29		90
	−6		36	
30		7		−51
	1		−15	
31		−8		38
	−7		23	
24		15		−40
	8		−17	
32		−2		7
	6		−10	
38		−12		23
	−6		13	
32		1		−8
	−5		5	
27		6		−10
	1		−5	
28		1		3
	2		−2	
30		−1		0
	1		−2	
31		−3		−4
	−2		−6	
29		−9		
	−11			
18				

and consists of 97 gravity meter stations located at $\frac{1}{8}$ mile intervals. Difference Tables were constructed for several station spacings and Equation (10) was applied. The results are shown in Figure 6 in which the probable errors, derived from second differences, are plotted as a function of station spacing, the maximum spacing being one mile. Extrapolation of the left hand end of the curve gives a probable error of approximately 0.2×10^{-4} C.G.S. Units. Studies of other Bouguer Gravity profiles in the Garber Area yielded similar results. The probable errors derived by this method were consistent with those obtained from a study of the original field notes taken during the course of the survey.

A Difference Table for a Seismograph Profile, taken from a map of the Viola horizon in the Guthrie Field, Logan County, Oklahoma,[7] is shown in Table 4. The profile (taken from Figure 5 of Swan's and Boyd's paper) is between Shotpoint 89, located at the southwest corner of Section 2, T-17-N, R-2-W, and Shotpoint 151, located at the southwest corner of Section 4, T-17-N, R-1-W. The interval between adjacent shotpoints is $\frac{1}{3}$ mile. The average values of the second difference, $\delta^2 t$, is 0.00973 seconds, which is equivalent to a probable error of 0.0034 seconds. If a velocity of 10,000 feet per second is assumed, the probable error of an individual depth calculation is 17 feet.

As an additional test of the method, a Difference Table taken from a Geochemical Survey[8] is shown in Table 5. This profile (see Figure 2 of Ransone's paper) starts at the northeast corner of Section 5 and traverses to the southeast corner of Section 47, all stations being located within the Deaf and Dumb Asylum Lands Block. The stations are located at intervals of $\frac{1}{4}$ mile. The unit for the Geochemical quantities is not defined. Differences up to and including the fourth order are given in the table. Application of Equation (10) to the four columns of differences gives values of 5.854, 5.343, 4.983 and 4.628 respectively for the first, second, third, and fourth order differences.

In the interpretation of geophysical maps or cross-sections it is sometimes desirable to compute derivatives of the function being measured. Several excellent papers[9–14] have recently been published on calculating derivatives of mag-

[7] B. G. Swan and W. B. Boyd, "Geophysical History of the Guthrie Field, Logan County, Oklahoma," *Geophysical Case Histories, Vol. 1*, Society of Exploration Geophysicists, Tulsa, Oklahoma (1948), pp. 301–311.

[8] W. R. Ransone, "Geochemical History of the Hardy Oil Field, Jones County, Texas," *Geophysical Case Histories, Vol. 1*, Society of Exploration Geophysicists, Tulsa, Oklahoma (1948), pp. 334–341.

[9] H. M. Evjen, "The Place of the Vertical Gradient in Gravitational Interpretations," *Geophysics, I*, No. 1 (January, 1936), 127–136.

[10] E. H. Vestine and N. Davids, "Analysis and Interpretation of Geomagnetic Anomalies," pp. 1–36, *Terrestrial Magnetism and Atmospheric Electricity*, Vol. 50, No. 1 (March, 1945), 1–36.

[11] D. C. Skeels and R. J. Watson, "Derivation of Magnetic and Gravitational Quantities by Surface Integration," pp. 133–150, *Geophysics, XIV*, No. 2 (April, 1949), 133–150.

[12] Leo J. Peters, "The Direct Approach to Magnetic Interpretation and Its Practical Application," *Geophysics, XIV*, No. 3 (July, 1949), 290–320.

netic and gravity functions. Since the formulae for derivatives are a function of the quantity being measured, it is possible to estimate the probable error in the computed derivative by applying the Law of Progression of Errors.

A convenient method of obtaining the derivatives of any smooth function is by application of Central Difference Formulae. For example, let u be measured at a series of equally spaced points as a function of the argument "a"; furthermore, let a Difference Table be constructed similar to the one shown in Table 1. Then the second derivative for the ith station may be calculated from the formula,[15]

$$w^2 f''(a) = \delta^2 u_i - \frac{1}{12}\delta^4 u_i + \frac{1}{90}\delta^6 u_i - \frac{1}{560}\delta^8 u_i + \cdots \tag{14}$$

where w is the station spacing

a is the argument

u is the measured function and $\delta^2 u$, $\delta^4 u$, etc., are even differences taken from the Difference Table in the same horizontal line with u.

Retaining the first two terms of Equation (14) gives,

$$f''(a) = \frac{u_{(i-2)}}{12w^2} + \frac{4u_{(i-1)}}{3w^2} - \frac{5u_i}{2w^2} + \frac{4u_{(i+1)}}{3w^2} - \frac{u_{(i+2)}}{12w^2} \cdots . \tag{15}$$

If it is assumed that the probable error, ϵ, is the same for each measured u, then the probable error in the derivative may be found by applying Equation (7) to the coefficients of the u's of Equation (15). The probable error in the derivative, so obtained, is $3.13\epsilon/w^2$.

If, in particular, the measured function, u, is harmonic, Laplace's Equation applies so that the second derivative with respect to the vertical may be readily calculated. Let measurements be made in two horizontal directions mutually perpendicular to each other and intersecting each other at a point. Laplace's Equation in rectangular coordinates may be written as,

$$\frac{\partial^2 u}{\partial z^2} = -\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right). \tag{16}$$

If the probable error is $3.13\ \epsilon/w^2$ for both $\partial^2 u/\partial x^2$ and $\partial^2 u/\partial y^2$, the probable rrror in $\partial^2 u/\partial z^2$ is $3.13\ \epsilon\sqrt{2}/w^2$.

SUMMARY

A method has been described for obtaining the approximate probable error existent in reduced geophysical quantities that is independent of original field

[13] Roland G. Henderson and Isidore Zietz, "The Computation of Second Vertical Derivatives of Geomagnetic Fields," *Geophysics, XIV*, No. 4, (October, 1949), 508–516.

[14] Thomas A. Elkins, "The Second Derivative Method of Gravity Interpretation," *Geophysics, XVI*, No. 1 (January, 1951), 29–50.

[15] Whittaker and Robinson, op. cit., p. 65.

notes. From the errors so obtained it is possible to estimate the probable error of computed functions, such as derivatives.

Whereas, in the illustrations shown, it was assumed that values of the measured function are available at a large number of equidistant points along a straight line, the method may be extended to a series of short linear segments where a statistical average leads to substantially the same results. In general, if the mth order of differences is being averaged it is necessary to have $(m+1)$ stations available in each linear segment. Other coordinate systems may also be used; for example, the method may be applied to quantities that are a function of an angle.

The few examples given are merely illustrative. The method may be applied to magnetic measurements in the field, the calibration of a magnetometer, and many other types of data collected in the field and in the laboratory.

THE EFFECT OF RANDOM ERRORS IN GRAVITY DATA ON SECOND DERIVATIVE VALUES*

THOMAS A. ELKINS†

ABSTRACT

Two random error grids were prepared using a set of 111 balls marked according to the Gaussian normal error law. For these grids, considered as grids of errors in gravity data, the second derivative values were computed and contoured. The resulting maps show strikingly the dangers in uncritical interpretations of second derivative maps based on insufficiently accurate data.

Statistical checks were applied both to the random error grids and to the computed second derivative values. The check on the latter necessitated the development of a theory of the correlation between second derivative values which is also applicable to many other quantities, besides second derivatives, which are computed by coefficients.

INTRODUCTION

The second derivative method of interpreting gravity data is a method of high resolving power. Consequently, it is very sensitive to errors in the gravity data used. This was realized early in the employment of the method at the Gulf Research Laboratory. Statistical studies of the effect of random errors in the gravity data were accordingly soon begun. This paper presents some of the interesting results of this work. These show how sheer random error anomalies can be mistaken for real structural anomalies if interpretations are made carelessly without attention to the accuracy of the gravity data used.

THE ERROR BALLS

The grids of random gravity errors to be used in the second derivative computations were made by drawing balls from a container. The balls were small ones of the same type as those used in a game called "pea pool." They were flat on one side, which made marking them easy, and were called "pills" by the firm which supplied them. Figure 1 is a photograph of a group of them.

A set of 111 of these balls was used. They were marked with values derived from the Gaussian normal error distribution with a probable error of 10 units, as shown in the table below:

Magnitude of Error	Numbers of Balls of Either Sign	Total Number of Each Magnitude
0		3
1 through 7	3 each	6 each
8 through 18	2 each	4 each
19 through 24	1 each	2 each
26, 28, 30, 34, 40	1 each	2 each
Total Number		111

* Presented at the Annual Meeting of the Society of Exploration Geophysicists at St. Louis, April 25, 1951. Manuscript received by the editor August 13, 1951.

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THE GRAVITY ERROR GRIDS

The balls were drawn one at a time, replacing each one before the next was drawn. The first grid, called Random Error Set A, was made by drawing the balls 361 times from a rectangular box. The result is shown in Figure 2. The table below compares the results found with those expected from the known composition.

Marking of Ball	Number Expected	Number Observed	
		Error Set A	Error Set B
−40, −34, −30, −28	13.0	15	13
−26, −24, −23	9.8	6	10
−22, −21, −20	9.8	15	10
−19, −18, −17	16.3	13	18
−16, −15, −14	19.5	16	19
−13, −12, −11	19.5	19	32
−10, −9, −8	19.5	27	23
−7, −6, −5	29.3	32	25
−4, −3, −2	29.2	37	32
−1, 0, +1	29.2	20	30
+2, +3, +4	29.2	36	29
+5, +6, +7	29.3	34	23
+8, +9, +10	19.5	13	13
+11, +12, +13	19.5	11	12
+14, +15, +16	19.5	27	16
+17, +18, +19	16.3	10	16
+20, +21, +22	9.8	6	13
+23, +24, +26	9.8	11	9
+28, +30, +34, +40	13.0	13	18

The question whether this distribution is of the random type which we wished to obtain can be studied by using a standard significance test called the "χ^2 test" (Fry, 1928). For the data of Error Set A in the table above, the value of χ^2 is 29.09 and the probability of this or a greater value of χ^2 is slightly less than 0.05. A value of 0.05 is often taken as a "level of significance" in statistics, and we can thus say that the grid we obtained is perhaps not random. It seems probable that the corners in a rectangular box will have a non-random effect despite all efforts at mixing.

Accordingly, another grid of 361 values, called Random Error Set B and shown in Figure 3, was prepared using a circular container which was a metal gravimeter top cover lined with felt. Figure 4 is a photograph of this container and some of the error balls. In the table above is a comparison of the results found in this drawing with those expected. The value of χ^2 is 19.85 and the

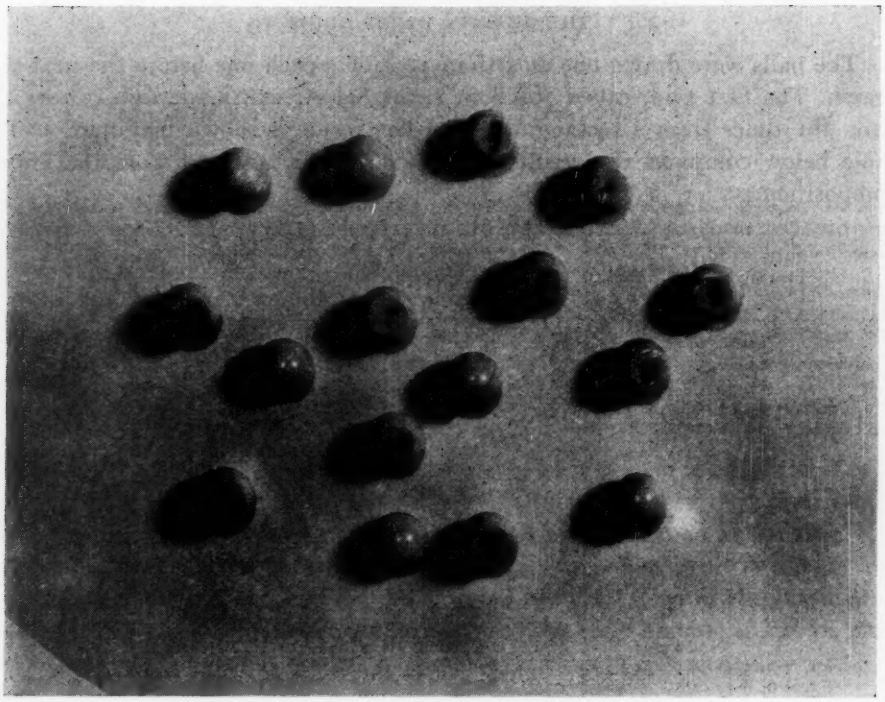

FIG. 1. Random error balls.

probability of this or a greater value is between 0.3 and 0.4. This result indicates that Error Set B is a good example of a random grid.

It is worth mentioning that this grid (Fig. 3) and perhaps also the grid first drawn (Fig. 2) may be useful for other problems in which random sets of errors are needed. Since a probable error of 10 units was used, it is easy to change over to any other probable error E by multiplying the values of the grid by $E/10$. For the second derivative computations, the unit was taken as 0.01 milligal. The probable error used was thus 0.1 milligal.

THE SECOND DERIVATIVE ERRORS

The second derivative was computed from the grids of Error Sets A and B, using the same procedures as are followed with field data. The formula employed was a previously published one (Elkins, 1951), the coefficient grid of which is shown in Figure 5. The gravity value, g_z, at each grid point is to be multiplied by the coefficient shown; the sum of the products is the second derivative value, $\partial^2 g_z/\partial z^2$, at P. To obtain values in cgs units, each coefficient must first be divided by $62k^2r^2$, where the grid spacing is r centimeters on a map scale of $1:k$.

The grids of second derivative values found, assuming the gravity values to be at half-mile spacing, are shown on Figure 6. Both error sets were used since,

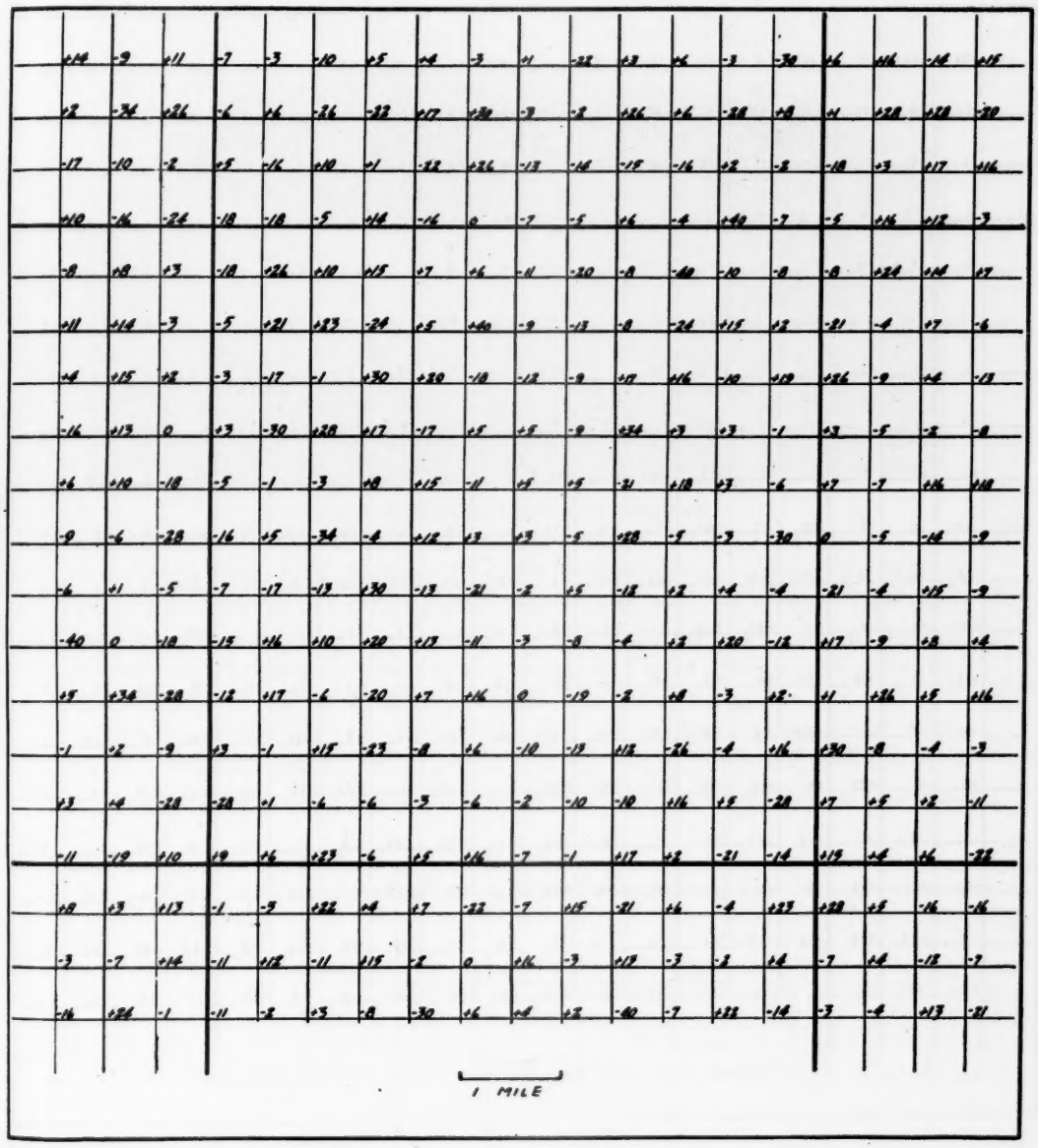

FIG. 2. Grid of random gravity errors—Random Error Set A. Gravity values are in 0.01-milligal units.

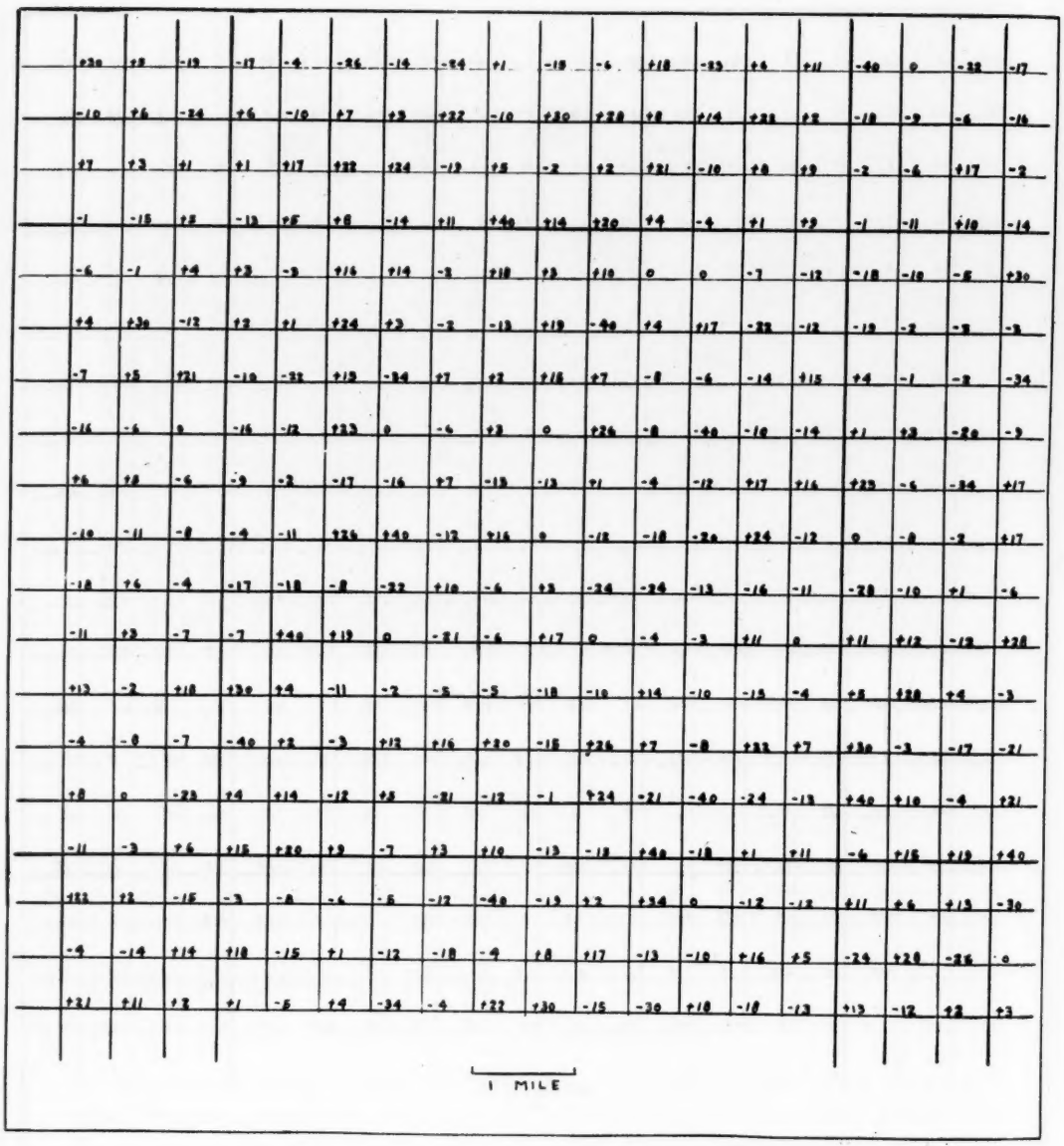

FIG. 3. Grid of random gravity errors—Random Error Set B. Gravity values are in 0.01-milligal units.

FIG. 4. Circular container for drawing balls.

even though Error Set A may not be a fair random sample, it is still worth while to study the second derivative picture for it as an example of what may occur under unusual circumstances. To avoid crowding the maps with detail, the mile and half-mile dividing lines have been omitted on Figure 6; the second derivative values shown are the values at the corners of this omitted grid.

The second derivative values of Figure 6 can easily be transformed to the values which correspond to other probable errors and spacings. If a probable error in the gravity data of E milligals is desired instead of 0.1 milligal, it is only neces-

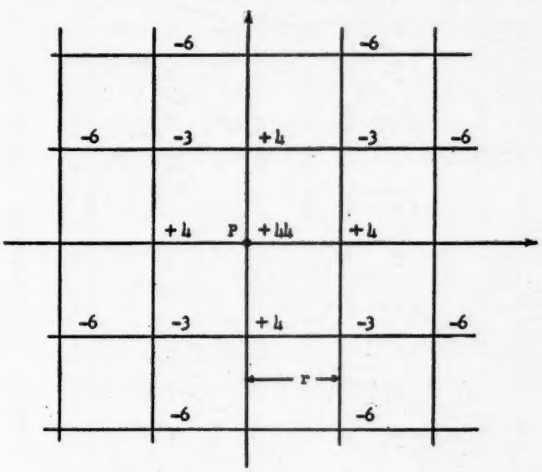

FIG. 5. Second derivative coefficient grid.

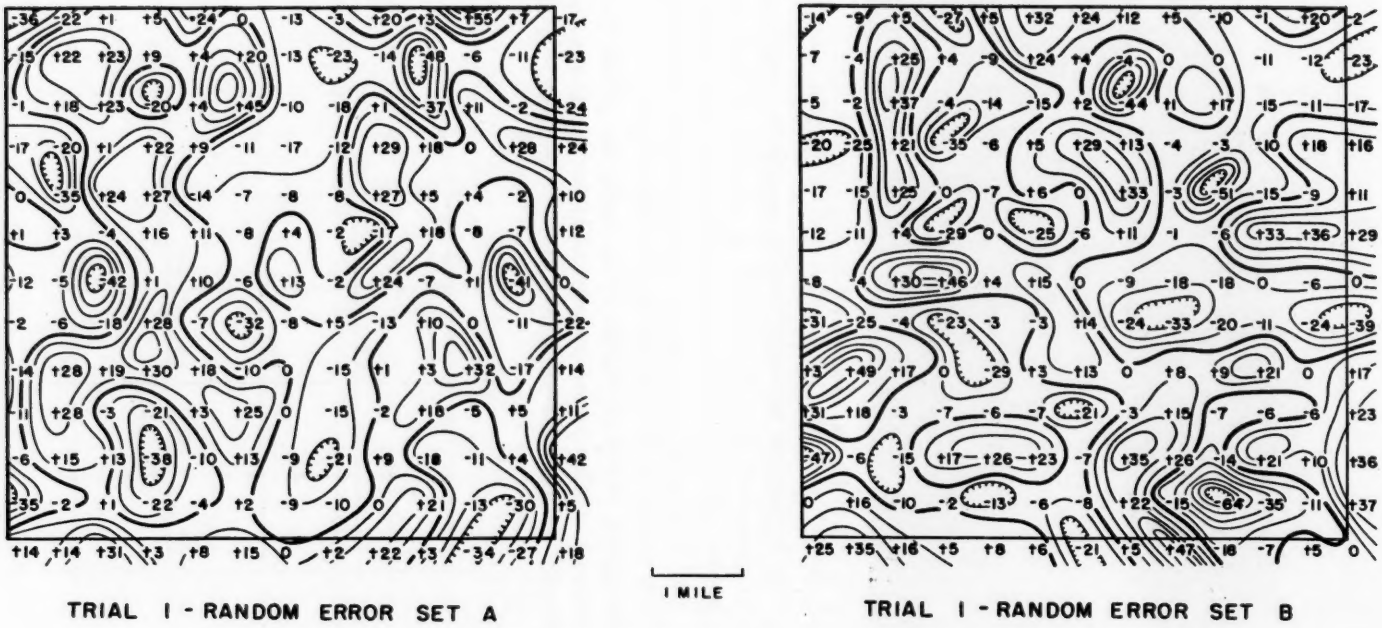

FIG. 6. Second derivative grids and contours for half-mile station spacing. Values are in 10^{-15} cgs units. Contour interval is 10×10^{-15} cgs unit.

sary to multiply the grid values by 10 E; if a spacing of M miles is desired instead of one-half mile, it is only necessary to multiply the grid values by $1/(4M^2)$. Figures 7 and 8 show maps prepared in this fashion for station spacings of $\sqrt{2}/2$ miles and one-mile respectively, keeping the probable error of the gravity data as 0.1 milligal. As with Figure 6, the mile and half-mile dividing lines have been omitted; the second derivative values refer to the corners of omitted grids of $\sqrt{2}/2$ and one-mile spacing respectively. Only a portion of the values of Figure 6 are used on Figures 7 and 8. They are identified in the following way. For each map of Figure 7 the values on the two diagonals running upward from the left bottom corner of the map which are closest to the center of the map are the first twelve values of the sixth and seventh rows from the top of the corresponding map of Figure 6 and the remaining values occupy the same relative positions as on Figure 6. For the maps of Figure 8 the upper left-hand quarters of the corresponding maps of Figure 6 were used. Obviously, many other maps can be constructed in a similar fashion for other spacings and probable errors.

The second derivative contours on Figures 6, 7, and 8 are interesting, even disturbing, because of the regular appearance of some of the anomalies. In fact, it is possible to outline excellent "trends" in some cases, for example, the high trend running vertically a little to the left of the center of the map for Error Set B in Figure 8. These contours show clearly the dangers in the interpretation of second derivative data if the errors in the original field data are unknown or ignored.

EVALUATION OF SECOND DERIVATIVE ANOMALIES

If a good estimate of the probable error of the Bouguer gravity values is available, it may be possible by a qualitative comparison of the second derivative map computed from the field data with a second derivative error map prepared from the grid values of Figure 6 to evaluate the anomalies by ruling out those which appear to be spurious. It is, of course, essential before making such comparisons to reduce the second derivative error map to the same gravity probable error, spacing, scale, and contour interval as the field map being studied. Occasionally, such a comparison might eliminate an actual anomaly, but this is unavoidable in any method based on probability considerations.

Parenthetically it is worth mentioning that a method of judging the reality of anomalies, which was previously published by the writer (Elkins, 1940), is not applicable here. The reason is that this method assumes that the values tested are independent in the statistical sense while, as will be shown in the next section, the second derivative values here studied are not independent. It is indeed possible to generalize the method referred to so that it will apply to these second derivative values, but the numerical calculations necessary appear to be excessive for practical use.

If we wish to study the effect of errors in the gravity data for some particular type of mass anomaly, such as a sphere, it is only necessary to add the second derivative errors to the second derivative values computed by the coefficients of

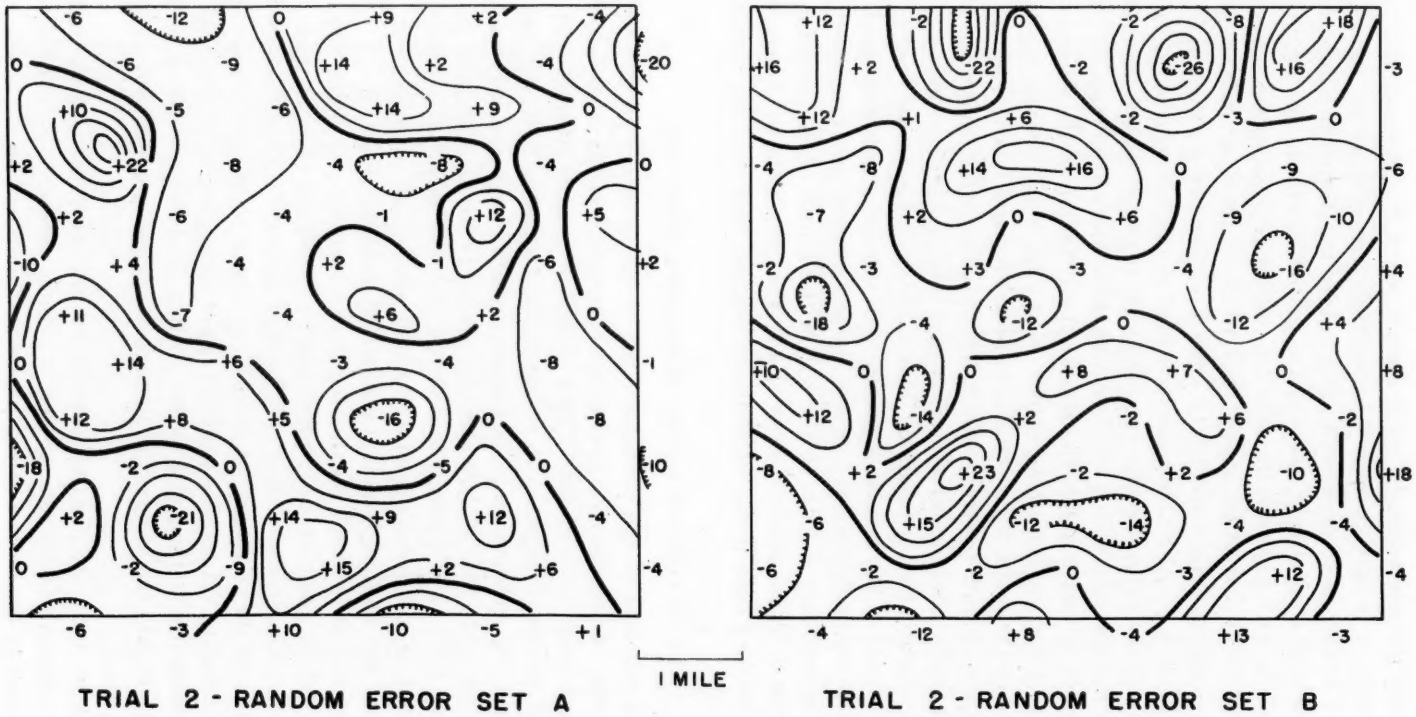

FIG. 7. Second derivative grids and contours for $\sqrt{2}/2$-mile station spacing. Values are in 10^{-15} cgs units. Contour interval is 5×10^{-15} cgs unit.

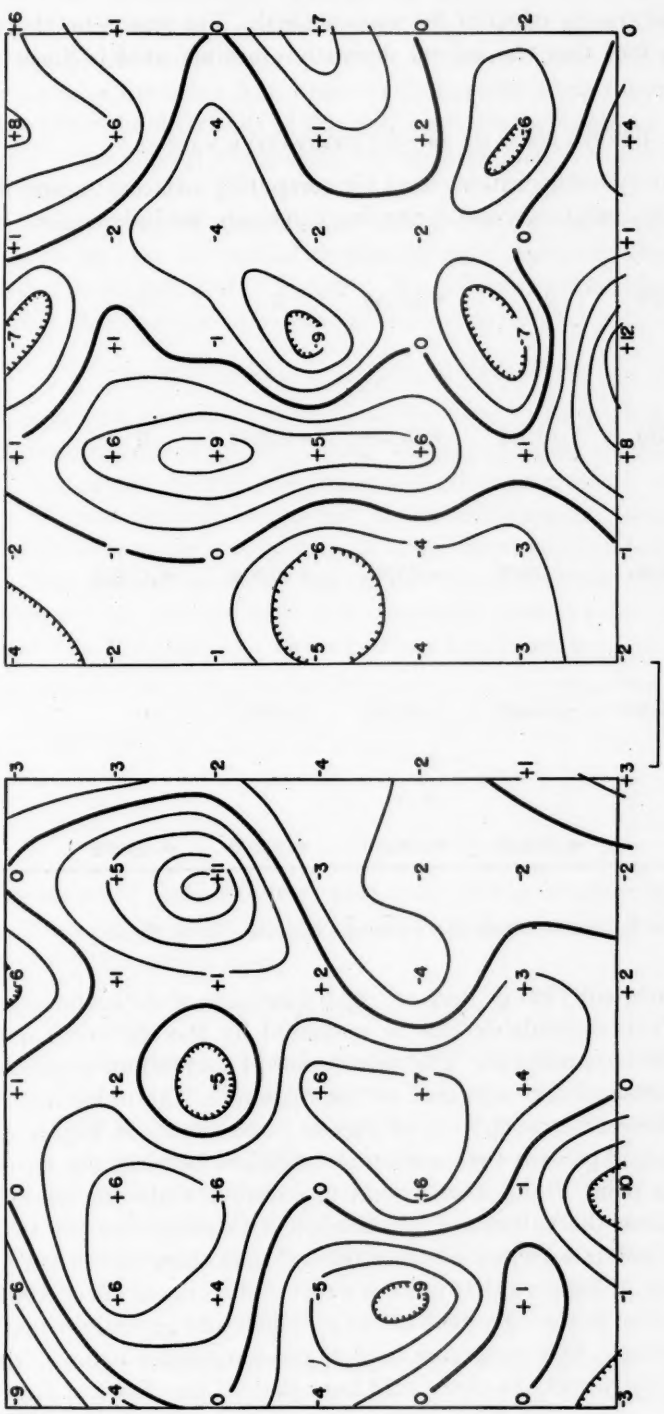

FIG. 8. Second derivative grids and contours for mile station spacing. Values are in 10^{-16} cgs units. Contour interval is 2.5×10^{-16} cgs unit.

Figure 5 from the gravity effect of the mass anomaly. The reason for this simple procedure is the fact that the second derivative formula used is linear in the gravity values.

CORRELATION OF SECOND DERIVATIVE VALUES

Since the gravity configurations used for computing adjacent second derivative values overlap, nearby second derivative values are not independent of each

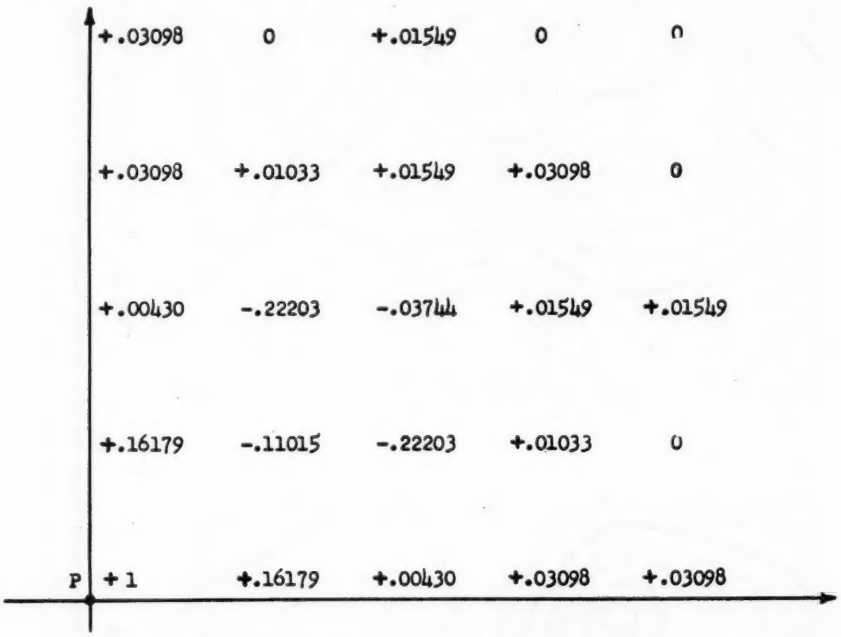

FIG. 9. Correlation coefficients for second derivative set of Figure 5.

other but are correlated. That is, they are related because of the common gravity values utilized. This dependence can be measured by the statistical quantity called the correlation coefficient. The calculation of correlation coefficients is lengthy, and is consequently relegated to the Appendix. The numerical results for the second derivative coefficients of Figure 5 are shown in Figure 9. The value shown at a grid point is the correlation coefficient between the second derivative values at point P and at the point in question. Only one quadrant of values is given since the values are symmetrical with respect to the two axes shown. Values at points a greater distance from *P* than those shown are zero.

It will be noted in Figure 9 that there is a sort of directional effect, the correlations being positive in the directions of the grid lines and generally negative in the diagonal directions. This may cause random error anomalies to have "trends" more often along the directions of the grid lines than in the diagonal directions.

This tendency may be seen in Figures 6, 7, and 8, especially in the maps for Error Set B, the better random sample of the two sets. It is especially striking in the map for Error Set B in Figure 8. It is worth while to remember this tendency to favor the directions of the grid when one is judging a second derivative anomaly or laying out the gravity survey preliminary to the second derivative computation.

It is perhaps worth stressing here that the numerical values of the correlation coefficients and on the second derivative error maps are those for the second derivative coefficient grid of Figure 5. If a different second derivative coefficient set is used, these numerical values will change, as may the consequent conclusions.

PROBABLE ERROR OF SECOND DERIVATIVE VALUES

Since second derivative formulas of the type of those shown in Figure 5 are linear combinations of gravity values, we may compute the theoretical probable error of the second derivative value from the known probable error of the gravity values. We use the well-known law of the propagation of errors; the probable error of the second derivative value is found merely by multiplying the probable error of the gravity values by the square root of the sum of the squares of the coefficients in the formula used. The computed value is listed in the table below, together with the actually observed values for Figure 6.

Error Set	Probable Error (in 10^{-15} cgs units)	
	Theoretical	Observed
A	12.0	12.2
B	12.0	13.2

The observed probable errors were computed by a customary formula, under the assumption of independence of the second derivative values. The formula becomes for this special case

$$\text{Probable error} = 0.0519\sqrt{\sum x^2},$$

where the summation is carried out over the 169 values of the grid. The details are given in the Appendix. The agreement is excellent for Error Grid A and fair for Error Grid B. However, we might wonder if greater errors would not be introduced by the assumption of independence when we know that the second derivative values are correlated. But it can be shown by a mathematical treatment, which because of its length is given in the Appendix, that mainly because of the large number of values (169) on the maps of Figure 6, the effect of the correlation is negligible.

CONCLUSION

The primary purpose of this paper is the presentation of the dangers in interpreting second derivative maps without checking the accuracy of the under-

lying gravity data. The natural looking but completely fictitious anomalies shown in Figure 8 are a graphic illustration of this point.

The results found have further been checked by a statistical treatment, mostly in the Appendix. Features of this treatment are the calculation of correlation coefficients for second derivative sets and the computation of probable errors for second derivative values, taking into account the existing correlation. The treatment here is general and may be applied to many other quantities, besides second derivatives, which are computed by coefficients.

ACKNOWLEDGMENTS

The writer is indebted for assistance received in carrying out this work and in preparing the figures to the following past and present members of the Gravity Interpretation Section of the Gulf Research & Development Company: Robert D. Craighead, William L. Dowler, Miss Gertrude Gruden, Mrs. Dorothy S. Hertz, Harry J. McGrew, and Miss Doris Jean Ristoff. When this work was started, the writer was a member of this section, which was under the direction of Dr. L. L. Nettleton; at present it is headed by Dr. Sigmund Hammer; to both the writer owes much in encouragement and assistance. The photographs were prepared by Clifford E. Boden. The writer also wishes to thank Dr. Paul D. Foote, Executive Vice President, Gulf Research & Development Company, for permission to publish this paper.

APPENDIX—THE CORRELATION BETWEEN SECOND DERIVATIVE VALUES

Introduction

The purpose of this appendix is to present an account of the correlation existing between second derivative values computed by coefficients. It will be obvious that for other quantities computed in a similar fashion by coefficients, the same methods may be used and corresponding conclusions drawn.

Formula for the Correlation Coefficient

Let the coefficients of a second derivative set be denoted by a_i, where i runs from 1 to n. Then the second derivative value at point P is $Y_P = \sum a_i X_{p_i}$, at point Q, $Y_Q = \sum a_i X_{q_i}$; where the X's represent gravity values and in the summation i runs from 1 to n. Although we shall speak of second derivative and gravity values for the sake of definiteness, the formula for the correlation coefficient which we shall derive in this section will hold for any set of coefficients a_i which yields some quantity, Y, as a linear function of other mutually independent quantities, $X's$, which have the same standard deviation.

Let r_{PQ} be the correlation coefficient between Y_P and Y_Q and σ_P and σ_Q the standard deviations of Y_P and Y_Q. Further let X_t' denote the quantity X_t less the mean value of X_t and Y_P' and Y_Q' the quantities Y_P and Y_Q less their respective mean values. Then

$$Y_P' = \sum a_i X_{p_i}' \quad \text{and} \quad Y_Q' = \sum a_i X_{q_i}'.$$

By definition,

$$r_{PQ} = \frac{\frac{1}{N}\sum Y_P' Y_Q'}{\sigma_P \sigma_Q},$$

where the summation is extended over the entire population of the N values taken by the product $Y_P'Y_Q'$. For simplicity we shall assume that the gravity values are all independent and have the same standard deviation, σ. Then

$$\sigma_P = \sigma_Q = \sigma\sqrt{a_1^2 + a_2^2 + \cdots + a_n^2}.$$

Also

$$Y_P'Y_Q = (a_1X_{p_1}' + a_2X_{p_2}' + \cdots)(a_1X_{q_1}' + a_2X_{q_2}' + \cdots)$$

and

$$\frac{1}{N}\sum Y_P'Y_Q' = \frac{a_1^2}{N}\sum X_{p_1}'X_{q_1}' + \frac{a_1a_2}{N}\sum X_{p_1}'X_{q_2}' + \cdots.$$

In the right hand side of the last equation, summations which involve two different points will equal zero since the X''s are independent and are measured from their mean values. A summation which involves the same point twice (say, when $p_r = q_s$) will occur when the gravity value for that point is common to the second derivative computations for both points P and Q. Summations of this kind will yield terms of the type $a_ra_s\sigma^2$. Therefore, the correlation coefficient between Y_P and Y_Q, when the X's are all independent and have the same standard deviation, is

$$r_{PQ} = \frac{\sum a_ra_s}{\sum a_i^2},$$

where by $\sum a_ra_s$ is meant the sum of the products of the coefficients of values X_m which are common to the second derivative computations for both points P and Q, and by $\sum a_i^2$ is meant the sum of the squares of all the coefficients of the second derivative set.

With the use of this formula, the correlation coefficients have been computed for the second derivative set of Figure 5. The numerical results are shown in the grid of Figure 9; the value shown at a grid point is the coefficient of correlation between the second derivative values at point P and at the point in question. Only one quadrant of values is given since the values are symmetrical with respect to the two axes shown. Values at points a greater distance from P than those shown are zero.

Probable Errors of Second Derivative Values

The probable error is defined as 0.6745 times the standard deviation. As is well known, for a theoretical distribution which satisfies the Gaussian normal

error law, the probable error represents a 50 percent probability; that is, it is the numerical value as likely as not to be exceeded in absolute value. Since the standard deviation is more commonly used in statistical theory, we shall base most of our formulas on it.

As a statistical check on the second derivative error grids, we wish to compare the theoretical standard deviation, σ, of the second derivative values with an estimate of σ derived from the computed second derivative values. The theoretical standard deviation may be computed from the known standard deviation of the gravity values. That is, by the well-known law of the propagation of errors, the standard deviation of the second derivative values is found by multiplying the standard deviation of the gravity values by the square root of the sum of the squares of the coefficients in the second derivative formula used.

To estimate σ from the computed second derivative values, we may use two well-known formulas, which assume the statistical independence of the values used, and which we shall state without further background since one is a special case of a more general formula which we shall shortly derive and the other has an analogous basis. Let σ_s denote the estimate of σ from our sample of n second derivative values, $x_1, x_2, \cdots, x_n$. The two formulas are

$$\sigma_s^2 = \frac{1}{n-1}\left[(x_1 - M)^2 + (x_2 - M)^2 + \cdots + (x_n - M)^2\right], \tag{1}$$

and

$$\sigma_s^2 = \frac{1}{n}\left[(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + \cdots + (x_n - \bar{x})^2\right], \tag{2}$$

where

$$M = \frac{1}{n}(x_1 + x_2 + \cdots + x_n), \tag{3}$$

and $\bar{x}$ is the known theoretical mean value of the population from which the sample was drawn. In our case $\bar{x}$ equals zero. Consequently, formula (2) for the probable error for this special case of 169 grid values reduces to

$$\text{Probable error} = 0.0519\sqrt{\sum x^2}, \tag{4}$$

where the summation is carried out over the 169 values. Since for our grids the values computed from formula (1) would differ by less than 0.3 percent from those computed by formula (2), there would have been no practical change had we used formula (1).

As remarked in the body of the paper, there is good agreement between the theoretical and observed probable errors. If we estimate the standard deviation of the probable error by the formula $0.6745\,\sigma/\sqrt{2n}$, which equals 0.4×10^{-15} cgs unit, the agreement is excellent for Error Set A and not too bad for Error Set B.

In fact, the agreement is so good that we wonder whether it should exist since we have applied formulas which assume the independence of the second derivative values when we know that these values are correlated. To explain this surprising agreement, the following study of the standard deviation for a sample of correlated values was made.

Consider n grid values $x_1, x_2, \cdots, x_n$, all of mean value $\bar{x}$, and standard deviation σ. Let r_{12} represent the correlation coefficient between x_1 and x_2, r_{13} that between x_1 and x_3, and so forth. Let the mean of the n grid values be M, as defined in equation (3). Then, by definition, the standard deviation, S, of the "sample" of n values, $x_1, x_2, \cdots, x_n$ is given by

$$S^2 = \frac{1}{n}\left[(x_1 - M)^2 + (x_2 - M)^2 + \cdots + (x_n - M)^2\right]$$

$$= \frac{1}{n}(x_1^2 + x_2^2 + \cdots + x_n^2) - M^2.$$

Now

$$M^2 = \frac{1}{n^2}(x_1^2 + x_2^2 + \cdots + x_n^2) + \frac{2}{n^2}(x_1x_2 + x_1x_3 + \cdots).$$

Therefore

$$S^2 = \frac{n-1}{n^2}(x_1^2 + x_2^2 + \cdots + x_n^2) - \frac{2}{n^2}(x_1x_2 + x_1x_3 + \cdots).$$

To derive an estimate of σ^2 we shall make use of what in statistical theory is known as the mean value or "expected" value of S^2, that is, the average value we should expect to find from a very large number of such samples of n grid values. We shall denote this "expected" value by $\overline{S^2}$. We then find, by making use of the definitions of σ and of the correlation coefficients and noting that there are $n(n-1)/2$ of the latter,

$$\overline{S^2} = \frac{n-1}{n}\sigma^2 - \frac{2\sigma^2}{n^2}(r_{12} + r_{13} + \cdots). \tag{5}$$

Let r be the average value of all the correlation coefficients, $n(n-1)/2$ in number. Note that in this enumeration we do not regard, say r_{21} as different from r_{12}. Then

$$\overline{S^2} = \frac{n-1}{n}(1 - r)\sigma^2.$$

From this we can derive an estimate of σ from our sample of n values, which we again denote by σ_s,

$$\sigma_s^2 = \frac{1}{(n-1)(1-r)}\left[(x_1 - M)^2 + (x_2 - M)^2 + \cdots + (x_n - M)^2\right].$$

This equation shows that on the average the standard deviation estimated from the observed grid values will be practically the same as that estimated in the case of no correlation at all between the observed values, provided that the average correlation coefficient, r, is small.

That this is the explanation of the paradoxical agreement referred to above of the observed probable errors computed on the basis of independence with the theoretical probable error will follow from the results of the next section, for it will there be shown that for a square array with $n = 169$, the value of r is of negligible magnitude.

The Average Correlation

The value of the average correlation, r, for any grid configuration can be computed from the definition by a rather lengthy process. We shall study here two simple types.

(*a*) *Set of points along a straight line.* Let n be the number of points in the line. Direct computation for a few values of n will easily establish the following formula for the coefficients of Figure 9 for $n \geqq 4$:

$$r = \frac{0.4561n - 0.7745}{n(n-1)}.$$

A study of the numerical values below and of the derivative of r with respect to n will show that, beginning at $n = 2$, r, which is always positive, steadily decreases to zero as n approaches infinity.

The values of r for a number of values of n are given below:

n	r
2	0.162
3	0.109
4	0.087
5	0.075
6	0.065
7	0.058
8	0.051
9	0.046
10	0.042
.	.
.	.
.	.
∞	0

(*b*) *Set of points in a square formation.* In developing the formulas we shall use the literal grid shown in Figure 10 instead of the actual numerical values of the correlations. This will simplify the algebra and the resulting literal formulas will then hold for this more general set of correlation coefficients, provided it is

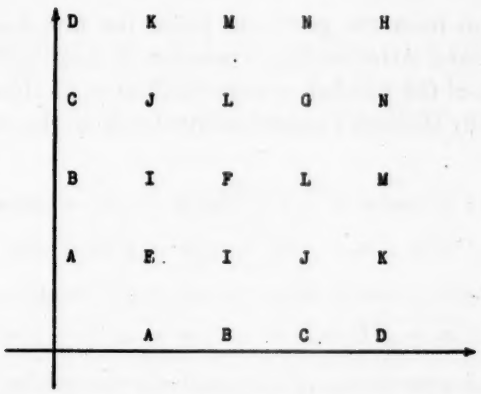

FIG. 10. Literal grid for average correlation coefficient computation.

symmetric with respect to both axes shown, with zero values at points more distant than those lettered. We denote by m the number of points in the side of the square array; by Z_m the sum of the correlation coefficients without repetition of the points of the square grid, that is, not regarding r_{21}, say, as distinct from r_{12}; and by r the average correlation coefficient as defined in the previous section. That is,

$$Z_m = \frac{m^2(m^2-1)r}{2}$$

for, since there are m^2 points in the square grid, there are now $m^2(m^2-1)/2$ different correlation coefficients.

m	General formula for Z_m	r for coefficients of Figure 9
2	$4A+2E$	0.071
3	$12A+6B+8E+2F+8I$	−0.021
4	$24A+16B+8C+18E+8F+2G+24I+12J+8L$	−0.026
5	$40A+30B+20C+10D+32E+18F+8G+2H$ $+48I+32J+16K+24L+12M+8N$	−0.021
6	$60A+48B+36C+24D+50E+32F+18G+8H$ $+80I+60J+40K+48L+32M+24N$	−0.016
7	$84A+70B+56C+42D+72E+50F+32G+18H$ $+120I+96J+72K+80L+60M+48N$	−0.013
...	...	...
13	$312A+286B+260C+234D+288E+242F+200G$ $+162H+528I+480J+432K+440L+396M$ $+360N$	−0.005

Direct calculation from the grids will prove the first four formulas for Z_m listed in the table above. After working these out, it is not difficult to check by a careful enumeration of the number of times each of the letters is involved as we proceed systematically through a square array of side m, that the general formula for $m \geqq 5$ is:

$$\begin{aligned} Z_m = {} & 2m(m-1)A + 2m(m-2)B + 2m(m-3)C + 2m(m-4)D \\ & + 2(m-1)^2E + 2(m-2)^2F + 2(m-3)^2G + 2(m-4)^2H \\ & + 4(m-1)(m-2)I + 4(m-1)(m-3)J + 4(m-1)(m-4)K \\ & + 4(m-2)(m-3)L + 4(m-2)(m-4)M + 4(m-3)(m-4)N. \end{aligned}$$

This formula also holds for $m=4$, as may easily be verified by checking it against the direct computation above. It is obvious from the general formula that the value of r approaches zero as m approaches infinity.

The general formula for Z_{13} in the table above was found from the formula just derived. The negligible value of r for a square grid with thirteen points on a side gives us a numerical check on the surmise made in the previous section, that it was the practically zero average correlation which caused the computed probable error of the correlated grid values to be nearly equal to the probable error theoretically expected in the case of no correlation at all.

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THE INTERPRETATION OF ELECTROMAGNETIC REFLECTION DATA IN GEOPHYSICAL EXPLORATION— PART I, GENERAL THEORY*

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ABSTRACT

It is shown that any variable current method of electrical exploration must be interpreted in terms of a semi-infinite conducting medium underlying a semi-infinite insulator. The complete theoretical treatment for a homogeneous conductor is outlined, and the details of the solution for low frequencies are presented. These indicate that the measured field intensities are not in-phase with the exciting current as has previously been assumed. These out-of-phase components from a homogeneous earth complicate the desired interpretation in terms of resistivity discontinuities at depth. The results of this paper provide a means of suitably correcting for this factor. Secondly, the insulating (air) region is shown to have an influence on the electromagnetic fields within the conductor. Thus, when considering the image approximation, the images are influenced by the air region and cannot be assumed to behave as they would in an infinite conductor. The lack of validity of this earlier assumption is demonstrated and suitable correction factors are derived. Specific results for the two cases of most practical interest are presented in graphical form. These are compared with experimental data obtained from a laboratory scaled model composed of metallic plates.

I. INTRODUCTION

The electromagnetic fields generated by an oscillating dipole located on the surface of a semi-infinite conductor have been extensively studied from several points of view. Sommerfeld (1909, 1926), Weyl (1919), and Niessen (1933), and others treated the general, formal solution and discussed various methods for evaluating the resulting integrals. The case of radiofrequency propagation in the insulating half-space has been studied and experimentally checked by many workers. This phase of the problem has been well summarized by Norton (1936, 1937) and Stratton (1941). Except for some theoretical discussions concerning the nature of the surface wave propagation, this aspect of the problem is in satisfactory agreement with experimental evidence when restricted to distances greater than a few wavelengths (as measured in the insulator). When both transmitter and receiver are on the conductor surface and when they are separated by a small fraction of an insulator wavelength, a different form of approximate solution is required. Such a form is needed when considering the transmission of audio frequencies along closely spaced wires near the earth's surface. These approximations were first reported by Foster (1931) in the form now generally used and have recently been reviewed by Sunde (1949), who lists a fairly complete bibliography on this subject.

In geophysical applications, the type of problem discussed by Foster (1931) is directly pertinent. However, in such cases, the desired result is information concerning the conductivity of the earth as a function of depth. For this, it is neces-

* Manuscript received by the editor September 6, 1951.

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sary to know in detail the fields within the interior as well as upon the surface of the earth. This problem has been approached by Riordan and Sunde (1933) and by Wolf (1946), both of whom obtained approximations to the complete problem for a two-layered conducting half-space.

In all electrical methods of geophysical exploration which employ time-varying currents, a study of the above problem becomes necessary in order to interpret the measurements made. Because of the many large resistivity variations in the sedimentary sections to be investigated, the complete problem must be stated as a very complicated boundary value problem. Exact solutions of such problems would involve a prohibitive amount of computation. Furthermore, uncertainties in the measurements as well as in the assumptions of homogeneity are too large to warrant such computations. Consequently, many investigations of variable current methods have been made on a strictly empirical basis. On the other hand, Evjen (1943), Lewis (1945), and Horton (1946), have discussed methods for interpreting such measurements based upon the assumption that large discontinuities in resistivity can be replaced by image oscillators. While such concepts are similar to those used in dc methods, they can be more properly labelled as reflections in view of the small phase velocities encountered in a conductor such as the earth. This approach is probably the most useful approximation that can be made to the complete problem. However, the work of this latter group contains two implicit assumptions that seriously impair the results when used to interpret experimental data. These are: 1) that the surface electromagnetic field of the surface oscillator is in phase with the oscillator current as long as the conductor is homogeneous; and 2) that the image oscillators can be considered to be embedded in an infinite conducting media rather than a semi-infinite one.

The purpose of this paper is to examine in considerable detail the electromagnetic fields within and on the surface of a semi-infinite, homogeneous conductor when such fields are produced by an oscillating dipole on the surface. From these results, it is apparent that the conducting half-space produces field components on the surface which are out-of-phase with the current even for a homogeneous conductor. Similarly, the insulating half-space modifies the fields within the conductor so that they are larger than for an infinite conductor. Thus, the earlier implicit assumptions are shown to be incorrect and are replaced by exact expressions for the field intensities. Within the approximation of this general image concept, the earth can be treated as a semi-infinite, homogeneous conductor containing various image oscillators. The field on the surface due to an image oscillator is exactly equivalent to the field at the image position due to a surface oscillator placed at the point of measurement. This fact follows from the reciprocity theorem. Consequently, the results developed here are adequate for the interpretation of alternating current exploration schemes insofar as the image approximation is valid. Finally, the results are expressed in sufficiently general terms to apply to any conducting medium. Because of this, it has been possible to experimentally verify the theory and computations by using a laboratory metallic

system which serves as a scaled model of a horizontally stratified earth. A subsequent paper will discuss this metallic model and show how it can be used to solve these boundary value problems in a matter of minutes as compared with the many days of computation required for each of the results presented in this paper.

II. HORIZONTAL, ELECTRICAL DIPOLE—SINUSOIDAL CURRENT

One of the most common means for producing variable electromagnetic fields for geophysical applications is an oscillator supplying current to a straight wire lying on the surface of the ground. The ends of this wire may or may not be conductively connected to the earth with electrodes, depending upon the frequency of the oscillator. If the field intensities are to be measured at points separated from the transmitter by distances much larger than the length of wire in the transmitter, this source may be considered as an oscillating electrical dipole. When this assumption is not valid and when pulsed currents are used instead of oscillatory ones, certain modifications become necessary and these are discussed in Section III. The fields, due to such an electrical dipole, were first obtained by Sommerfeld (1909, 1926). These formal expressions have been reduced to a form applicable to geophysical work by several writers [Foster (1931), Riordan and Sunde (1933), and Wolf (1946)] and are reproduced below.

These results have considerable generality and are subject only to the following assumptions: (i) Maxwell's equations are a valid description in both the air and the earth; (ii) the tangential components of $\vec{E}$ and $\vec{H}$ are continuous across the boundary; (iii) the limit of $\vec{H}(\omega)$ as ω approaches zero is $H(0)$, given by Biot-Savart's Law (ω is the angular frequency of the exciting current); (iv) the distances of interest are very small compared to a wavelength as measured in the air, so that all phase shifts in the air may be neglected (i.e., ϵ (air) is assumed equal to zero); and (v) $\omega\epsilon/\sigma \ll 1$, where ϵ is the dielectric constant of the earth ($< 10^{-9}$ farads/meter) and σ is the conductivity of the earth ($> 10^{-4}$ mhos/meter) when averaged over typical sedimentary sections. Using these, any of the field intensities can be expressed in the form given by Foster (1931). It is sufficient here to consider only E_x, the electrical field intensity parallel to the exciting dipole. Thus:

$$E_x = \frac{-I_M e^{i\omega t} l_e}{2\pi\sigma}\left(\frac{\partial^2 P}{\partial z^2} + \frac{\partial^3 Q}{\partial y^2 \partial z}\right) \tag{1}$$

where

$$P(r, z, k) = \frac{e^{ik\sqrt{z^2+r^2}}}{\sqrt{z^2+r^2}} \tag{2}$$

and

$$Q(r, z, k) = I_0\left(\frac{-ik}{2}\left[\sqrt{r^2+z^2}+z\right]\right) K_0\left(\frac{-ik}{2}\left[\sqrt{r^2+z^2}+z\right]\right). \tag{3}$$

In these expressions: $r^2=x^2+y^2$, k is the propagation constant of the earth ($k^2=i\omega\mu\sigma$), I_0, and K_0 are modified Bessel functions of the first and second kind, and I_M is the amplitude of the current in the dipole of length l_c.

If $I(t)=I_0 \cos wt$, solutions of (1) can be superimposed to obtain the real quantity

$$E_x = A_x \cos(\omega t - \Delta_x) \tag{4}$$

wherein A_x and Δ_x are obtained from (1) by the usual methods. Numerical solutions for A_x and Δ_x have been obtained for several geometrical arrangements of the transmitter and receiver. The general features of all solutions can best be demonstrated by considering the details of E_x in the plane which forms the perpendicular bisector of the transmitting element [i.e., $x=0$ in Equations 1, 2, and 3 and denoted by $E_x(y, z, t)$]. Now, when $\omega=0$, $\Delta_x=0$, and A_x becomes the field component for the dc case, or $A_x(0)=I_M l_c/2\pi\sigma R^3$. Hence, in the following it is more convenient to write $A_x=A_x(\omega)/A_x(0)$ and consider $A_x(0)$ as a normalizing factor. When this is done, A_x becomes a function of kR ($R^2=y^2+z^2$) and θ only, where θ is the angle of propagation into the conductor (i.e., the angle between the surface and the line connecting the transmitter and receiver). The special case of $\theta=0$ will be referred to as boundary wave propagation, since both transmitter and receiver are then on the boundary of a homogeneous conductor.

Two important facts are apparent from the above analysis. First, since the functions of interest depend only upon kR and θ, a scaled model can be built in which kR is held constant. From the definition of k, it is apparent that this can be accomplished by properly varying σ, μ, or ω. Some of the experimental results shown in the following sections were obtained with such a model in which σ was the quantity chosen for modeling. The construction and use of this model will be described in a subsequent paper. The second factor of importance is that a set of curves or tables giving A_x as a function of kR for various values of θ provides all of the correct information for interpreting experimental results in terms of the image approximation. The boundary wave function provides the correct response for a homogeneous earth, and each discontinuity can be replaced by an image oscillator. The propagation between any one image oscillator within the earth and the receiver on the surface is given by that curve corresponding to the correct value of θ. Hence, such a set of curves will provide all the additional information needed to interpret ac measurements according to the same scheme used for dc (resistivity) methods.

The details of reducing (1) and (4) to suitable computational form are too long for reproduction here. Hence, we shall summarize the method and state the final results. The variable, kR, is a complex quantity and can be written as

$$kR = (1+i)R\sqrt{\omega\mu\sigma/2} = (1+i)\xi, \tag{5}$$

where ξ is the "numerical distance," $2\pi R/\lambda$, λ being the wavelength in the conductor. Substituting this along with (2) and (3) into (1), one obtains the normal-

ized form of E_x for this case written as

$$E_x = e^{i\omega t}[F(\xi) - iG(\xi)], \tag{6}$$

where $F(\xi)$ and $G(\xi)$ are real functions. Then, the desired functions in (4) become

$$\begin{aligned} A_x(\xi) &= \sqrt{F^2(\xi) + G^2(\xi)}, \\ \Delta_x(\xi) &= \tan^{-1}(G/F). \end{aligned} \tag{7}$$

Since the arguments of the two types of Bessel functions in (3) are not the same when $z \neq 0$, the resulting expressions for F and G in (6) are rather long. Hence, the desired normalized form of E_x can best be written in complex form, from which the obtention of F, G, A, and Δ follows from (6) and (7). Thus:

$$E_x = E_0 e^{i\omega t}[T_1 + T_2 I_0 K_0 + T_3 I_0 K_1 + T_4 I_1 K_0 + T_5 I_1 K_1] \tag{8}$$

where:

$$\begin{aligned} T_1 &= e^{ikR}[g^2(3 - 3ikR + k^2R^2) + (ikR - 1)], \\ 2T_2 &= k^2R^2(3g^2 - 2), \\ 2T_3 &= ikR(3g^2 - 2)(1 + g) + ik^3R^3g(1 - g^2), \\ 2T_4 &= ikR(3g^2 - 2)(1 - g) - ik^3R^3g(1 - g^2), \\ 2T_5 &= k^2R^2g(4 - 3g^2), \end{aligned} \tag{9}$$

$$g = \sin\theta = \frac{z}{R}, \tag{10}$$

the argument of I_0 and I_1 is $-ikR/2(1+g)$, and that of K_0 and K_1 is $-ikR/2(1-g)$. The I and K functions can be expressed in terms of J and Y functions, where the arguments are of the form $xe^{\pi i/4}$. These latter functions are adequately tabulated by the National Bureau of Standards (1943, 1950).

In Figure 1, the normalized $A_x(\xi)$ functions are plotted against ξ for five values of g (or θ). These values have been chosen so as to permit interpolation for most geophysical applications. The corresponding phase angle functions, Δ_x, have been plotted in Figure 2. An examination of these curves indicates the magnitude of the errors involved in assuming an infinite (rather than semi-infinite) conductor. In the first place, the phase shifts for $\theta = 0°$ (i.e., along the boundary) are sufficiently large for small values of ξ that they cannot be neglected. Secondly, the phase shifts are markedly different for various angles into the conductor. These deviations from the values predicted for an infinite conductor are largest for small values of θ, i.e., shallow reflectors, where the amplitudes are largest. Therefore, in calculating the effect of various images, the correct angle must be used.

III. PULSED CURRENTS AND LONG LINEAR TRANSMITTERS

The results presented in the previous section provide the basic information necessary for interpreting the various ac exploration methods. However, certain

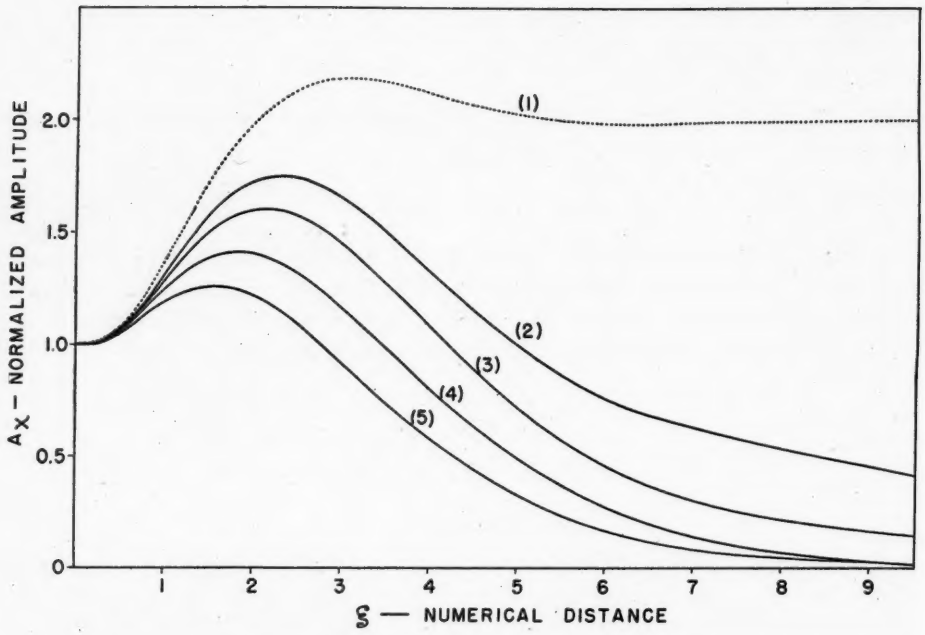

FIG. 1. Normalized amplitudes, A_χ, of electrical field strength along the boundary of and into a conductor as a function of numerical distance, $\xi = 2\pi R/\lambda = R(\omega\mu\sigma/2)^{1/2}$. Angles, θ, between surface and direction of propagation for different curves are: Curve 1, $\theta = 0°$; Curve 2, $\theta = 10°$; Curve 3, $\theta = 17°1'51''$; Curve 4, $\theta = 35°15'45''$; Curve 5, $\theta = 90°$.

extensions are necessary if the application is to be direct. In the first place, input currents are not always sinusoidal, and a Fourier synthesis must be made for any particular type of input current. While this method is straightforward for an arbitrary form of input current, the details frequently become quite involved. In this section, we shall consider the extension to square pulses of input current—a form frequently used in geophysical exploration. In the second place, the electrical cable used for the transmitter is frequently too long or arranged non-linearly so that it cannot be considered to be a dipole. In such cases, it is necessary to consider the transmitter to be composed of many dipole elements and to sum (or integrate) the fields from these individual elements. The results of such an extension to a linear cable of arbitrary length are given in this section. Extensions of these types can be made for both the boundary wave and for the various images considered. Since the image method is already an approximation, sufficient detail is usually acquired without summing individual dipole contributions. Such results can be obtained more readily from a model of the type previously mentioned. However, the boundary wave contributes a large fraction of the total measurement and requires this more detailed correction in order to adequately interpret any ac data. In particular, the work of Evjen (1943), Lewis (1945), and Horton (1946), in which such boundary waves are assumed to be in-phase with

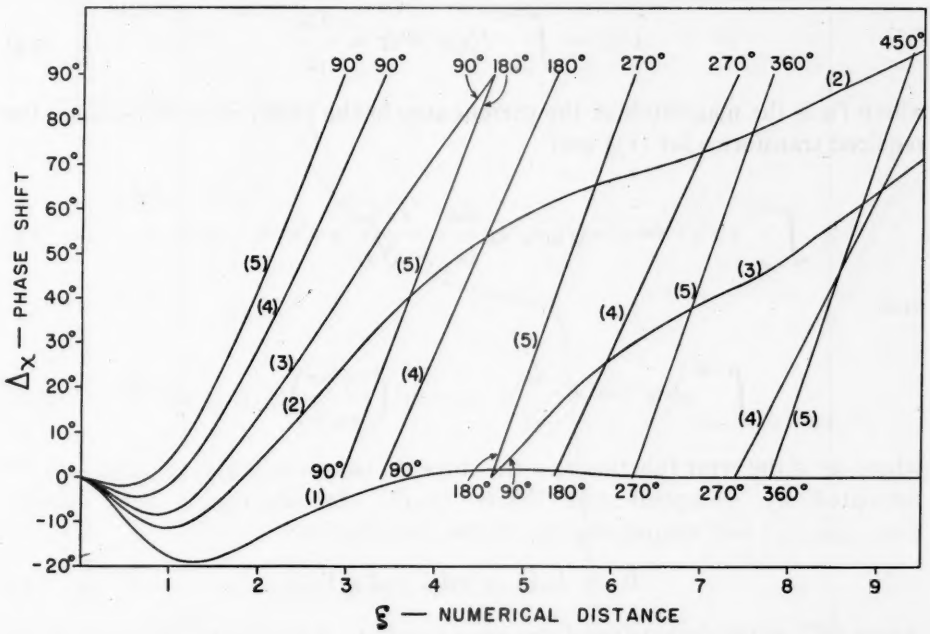

FIG. 2. Phase shift, Δx, for electrical field strength along the boundary of and into a conductor as a function of numerical distance, $\xi = 2\pi R/\lambda = R(\omega\mu\sigma/2)^{1/2}$. Angles, θ, between surface and direction of propagation for different curves are: Curve 1, $\theta = 0°$; Curve 2, $\theta = 10°$; Curve 3, $\theta = 17°1'51''$; Curve 4, $\theta = 35°15'42''$; Curve 5, $\theta = 90°$.

the current, requires adequate correction factors. Hence, the details of the electrical fields on the surface of a homogeneous conductor, as presented in this section, should have direct utility.

When the transmitter and the point of measurement are both on the surface ($z = 0$), equation (8) reduces to the simpler form:

$$E_x = E_0 e^{i\omega t}\left\{e^{ikR}(ikR - 1) - ikR[I_0K_1 + I_1K_0]\right\} \tag{11}$$

where the arguments of all four Bessel functions are $-ikR/2$. According to Watson (1945)

$$I_0(x)K_1(x) + I_1(x)K_0(x) = \frac{1}{x}; \tag{12}$$

it follows that

$$E_x = E_0 e^{i\omega t}\left\{e^{ikR}(ikR - 1) + 2\right\}. \tag{13}$$

Now, a square pulse can be considered to be a positive unit step-function, followed by a negative unit step-function, but separated in time by the pulse length. Hence, it is sufficient to consider the Fourier transform of (13), corresponding to a single step function. The required transform for the input current, $I(t)$, is

$$I(\omega) = \int_{-\infty}^{+\infty} I(t)e^{-i\omega t}dt = \frac{I_M}{i\omega} \tag{14}$$

where I_M is the magnitude of the current step in the pulse. Since $k=\sqrt{i\omega\mu\sigma}$, the required transforms for (13) are:

$$\int_{-\infty}^{+\infty} e^{i\omega t}e^{-r\sqrt{\mu\sigma}\sqrt{i\omega}}r\sqrt{\mu\sigma}\sqrt{i\omega}\frac{d\omega}{i\omega} = \frac{r\sqrt{\mu\sigma}}{\sqrt{\pi t}}e^{-r^2\mu\sigma/4t}, \quad (t > 0) \tag{15}$$

and

$$\int_{-\infty}^{+\infty} e^{i\omega t}e^{-r\sqrt{\mu\sigma}\sqrt{i\omega}}\frac{d\omega}{i\omega} = 1 - \operatorname{erf}\left(\frac{r\sqrt{\mu\sigma}}{2\sqrt{t}}\right), \quad (t > 0) \tag{16}$$

where *erf* is the error function and the three transform in (14), (15), and (16) are tabulated by Campbell and Foster (1948). Introducing a new variable $\zeta=r\sqrt{\mu\sigma}/2\sqrt{t}$ and simplifying the results, one obtains:

$$E_x = E_0\{1 + \operatorname{erf}\zeta - \zeta \operatorname{erf}'\zeta\} \tag{17}$$

where $\operatorname{erf}'\zeta$ is the derivative of the error function. A similar result has been obtained by Riordan (1931). Since tables of the error function and its derivative are readily available, it is possible to calculate the electrical fields for this particular geometry corresponding to any prescribed type of square-pulsing system.

Equation (17) represents the electrical field component parallel to an input current element. If the current element is long, it is necessary to integrate this expression over the entire length of the transmitter cable. Furthermore, the measured voltage is a similar integral over the length of the receiver cable, used for measuring the field strength. Thus, for this case, the voltage can be expressed as a double integral that can be evaluated in closed form. If dx_1 is the element of current cable parallel to the x-axis and dx_2 a similar element of the voltage measuring cable and the two are separated by a distance $r=[y^2+(x_1-x_2)^2]^{1/2}$, this integral becomes:

$$\begin{aligned} V &= \frac{I_M}{2\pi\sigma}\int_{P_1}^{P_2} dx_2 \int_{c_1}^{c_2} [1 + \operatorname{erf}\zeta - \zeta \operatorname{erf}'\zeta]\frac{dx_1}{r^3} \\ &= V_0 + \frac{I_M}{2\pi\sigma y^2}\sum_{i=1}^{2}\sum_{j=1}^{2}(-1)^{i+j}[r_{ij}\operatorname{erf}(\gamma r_{ij}) - e^{-\gamma^2 y^2}x_{ij}\operatorname{erf}(\gamma x_{ij})] \end{aligned} \tag{18}$$

where $r\gamma=\zeta$, r_{ij} are the distances between one end of the current cable and one end of the voltage measuring cable, x_{ij} is the x-component of r_{ij}, and V_0 is the voltage measured with dc input. In applying this equation, there are no restrictions on the geometrical arrangement of cables, except that the current carrying cable must be parallel to the voltage measuring cable. However, in the so-called

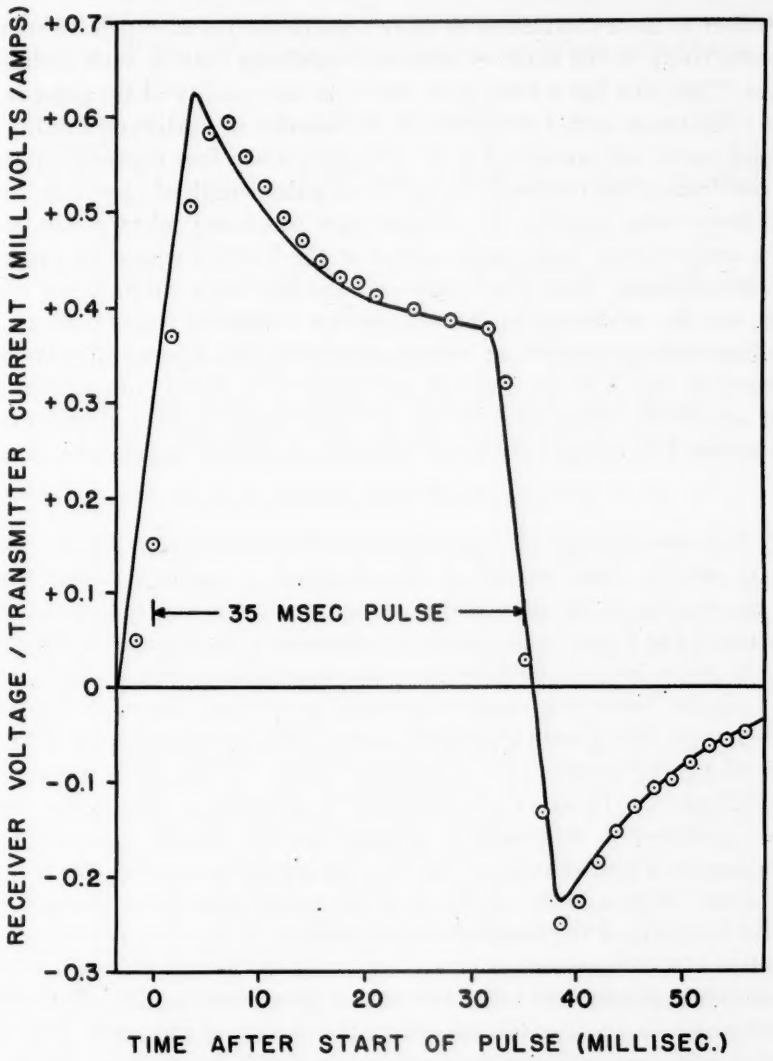

FIG. 3. Signal transmitted 2,000′ along a homogeneous earth having a conductivity =0.1025 mhos/meter when transmitter signal is a 35 millisecond square pulse. Solid curve computed from Equation 18. ○ values are experimental data from Fort Bend County, Texas.

Wenner arrangement, where $y=0$, (18) becomes indeterminate as written. In this case, the value of the limit, as $y \to 0$, can be readily obtained.

Numerous examples of (18) have been computed in the author's laboratory for various geometrical arrangements, conductivities, and pulse lengths. Such results represent the contribution of a homogeneous earth to the total voltage measured as a function of time. Consequently, it is necessary to correct all field measurements for this effect before a proper interpretation can be made in terms

of the effect of more conductive or more resistive bodies at depth. In some areas, the conductivity of the earth is sufficiently uniform that no such bodies are detectable. Then, one has a very good check on the validity of the present theory. Figure 3 illustrates such a situation for one location in Fort Bend County, Texas. The solid curve was computed from (18) for a 1,000 foot transmitter separated 2,000 feet from a 500 foot receiver and for a pulse length of 35 milliseconds. The conductivity value used in this computation was 0.103 mhos/meter, since this was the conductivity of the shale section at the location where the experimental data were obtained. The circles represent the field data without any correction factors, but the measuring equipment yields a voltage averaged over an interval of 7 milliseconds rather than an instantaneous one. The theoretical curve has been computed on this basis in order to permit a more direct comparison. Finally, similar agreement, obtained with the metallic model, further checks the theory and provides a direct proof that the metallic model is a satisfactory one.

IV. LOOPS USED AS MAGNETIC DIPOLE

Another common type of transmitter and receiver for geophysical applications is a loop antenna small enough to be considered a magnetic dipole. Instead of using the results of the previous sections and integrating the electrical dipole fields around the closed loops, the loop is assumed to be a magnetic dipole. Then, magnetic dipole fields are obtained in a manner paralleling the development for an electric dipole. These loops may be oriented in various ways with respect to the earth's surface, but practical considerations necessitate having the plane of the loop on the earth's surface, i.e., horizontal loops. The magnetic dipole is then a vertical dipole, i.e., its axis is perpendicular to the surface. This is the only orientation considered in this section, although results can be obtained for other orientations by a similar analysis. Briefly, the argument for using horizontal loops is as follows. With a given electrical power and a given mass of copper for the wire, the intensity of the magnetic field produced by a coil is proportional to the coil radius and independent of any other variables. Hence, to produce (or measure) fields for geophysical investigations at great depths, the coil becomes too large to mount in any position except on the surface of the earth. Such coils are also most useful in working with horizontally stratified metallic models due to the nature of the electrical fields produced.

In order to derive suitable expressions for the magnetic fields of a magnetic dipole on the boundary of a semi-infinite conductor, one proceeds in a manner similar to that of Section II. Sommerfeld's (1926) expression for the vertical component of such a field can be reduced to a form similar to (1) by the same methods used in deriving (1). In this case, the result is:

$$H_z^* = \frac{I_M A_T N_T e^{i\omega t}}{2\pi}\left\{-\frac{\partial^2 P}{\partial z^2} - \frac{1}{k^2}\frac{\partial^4 P}{\partial z^4} + k^2\frac{\partial Q}{\partial z} + 2\frac{\partial^3 Q}{\partial z^3} + \frac{1}{k^2}\frac{\partial^4 Q}{\partial z^4}\right\} \qquad (19)$$

where A_T is the area of the transmitting coil, N_T is the number of turns, and all

of the other symbols are the same as in (1). Equation (19) can be reduced to a form similar to (8) by performing the indicated operations, and the result is:

$$H_z^* = \frac{I_M A_T N_T e^{i\omega t}}{2\pi R^3}\{G_1 e^{ikR} + G_2 I_0 K_0 + G_3 I_1 K_1 + G_4[I_0 K_1 + I_1 K_0] + G_5[I_1 K_0 - I_0 K_1]\} \quad (20)$$

where:

$$\begin{aligned}
k^2R^2G_1 &= (ikR - 1)(105g^4 - 90g^2 + 9) + k^2R^2(45g^4 - 39g^2 + 4) \\
&\quad - ik^3R^3(10g^4 - 9g^2 + 1) - k^4R^4(g^4 - g^2) \\
2G_2 &= 3g(35g^4 - 30g^2 + 3) - k^2R^2g(5g^4 - 7g^2 + 2), \\
2G_3 &= -5g(21g^4 - 32g^2 + 11) + k^2R^2g(5g^4 - 8g^2 + 3), \\
2ikRG_4 &= 3(35g^4 - 30g^2 + 3) - k^2R^2(10g^4 - 7g^2), \\
2ikRG_5 &= 3g(35g^4 - 30g^2 + 3) - k^2R^2(45g^4 - 58g^2 + 16) \\
&\quad + k^3R^3g(g^4 - 2g^2 + 1),
\end{aligned}$$

where all of the quantities are defined as in (9).

In order to reduce (20) to a form suitable for computation and subsequent interpretation, it is necessary to note that the voltage measured by a detecting loop is (within the dipole approximation):

$$V^* = A_R N_R \frac{\partial B_Z^*}{\partial t} = i\omega\mu A_R N_R H_Z^* \quad (21a)$$

$$= \frac{A_R N_R H_0 \xi^2}{\sigma} e^{i\omega t}\{F_Z^*(\xi) - iG_Z^*(\xi)\} \quad (21b)$$

$$= \frac{A_R N_R H_0}{\sigma} \xi^2 A_Z^*(\xi) \cos\left(\omega t - \Delta_Z^* + \frac{\pi}{2}\right) \quad (21c)$$

where A_R and N_R are the area and number of turns, respectively, of the receiving loops, and H_0 is the magnetic field strength for dc. Thus, it is possible to compute the more general functions $(\xi^2 Az^*)$ and Δz^* for various values of g. Then, these can be applied to any given experimental case by first computing ξ and the normalization factor H_0 of (21c). In Figure 4, the normalized amplitude functions (Az^*) are plotted as functions of ξ for four different values of g (i.e., for angles of transmission into the conductor.) The normalization factors, H_0, are simply the magnetic field strength for the given geometry with dc current in the coil. Hence, they are functions of θ as well as R in this case, whereas in Section II, those normalization factors were independent of θ. In Figure 5, the total phase shift, Δ^*, is plotted for the boundary wave ($\theta = 0$) and for $\theta = 10°$. For larger angles, the curves are nearly linear as in the case of Δ_x (Fig. 2) and hence are not reproduced here.

There are certain similarities between these results for a magnetic dipole and

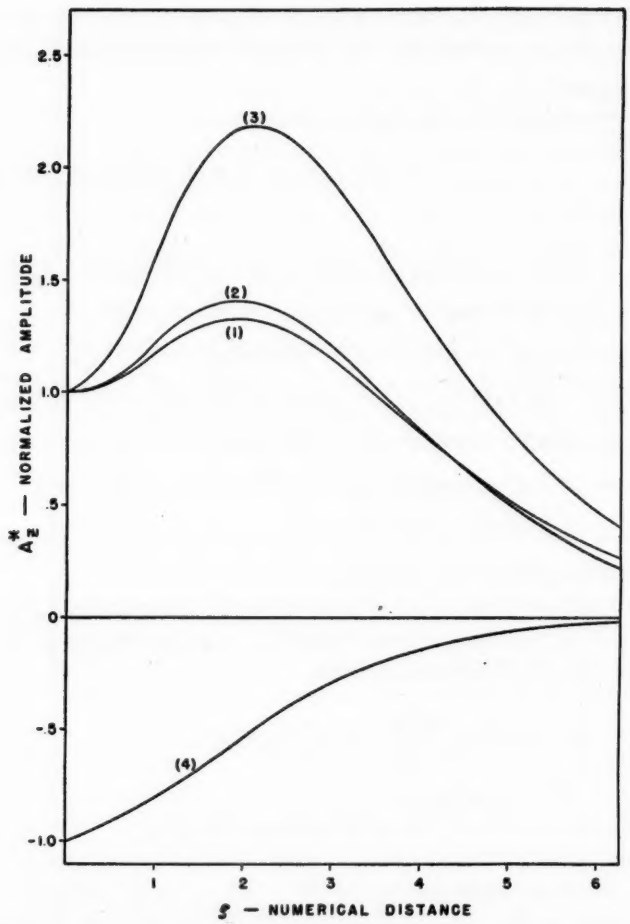

FIG. 4. Normalized amplitudes, A^* (magnetic field strength due to a magnetic dipole), for propagation along the boundary of and into a conductor as a function of numerical distance, $\xi = 2\pi R/\lambda = R(\omega\mu\sigma/2)^{1/2}$. Angles, θ, between surface and direction of propagation for different curves are: Curve 1, $\theta = 0°$; Curve 2, $\theta = 10°$, Curve 3, $\theta = 25°44'$; Curve 4, $\theta = 90°$.

those in Figures 1 and 2 for an electric dipole. However, it must be emphasized that the fundamental difference is due to the orientation of the transmitting and receiving dipoles with respect to each other and with respect to the boundary. For the same orientations, the magnetic field of a magnetic dipole is the same as the electric field of an electric dipole. It is this similarity that allows one to make very broad use of the specific curves plotted. In order to indicate the validity of these results, some of the magnetic dipole results are compared with experimental measurements with a metallic model in Figures 6 and 7. These tests consisted of measuring the voltage in a receiving loop due to sinusoidally varying current in

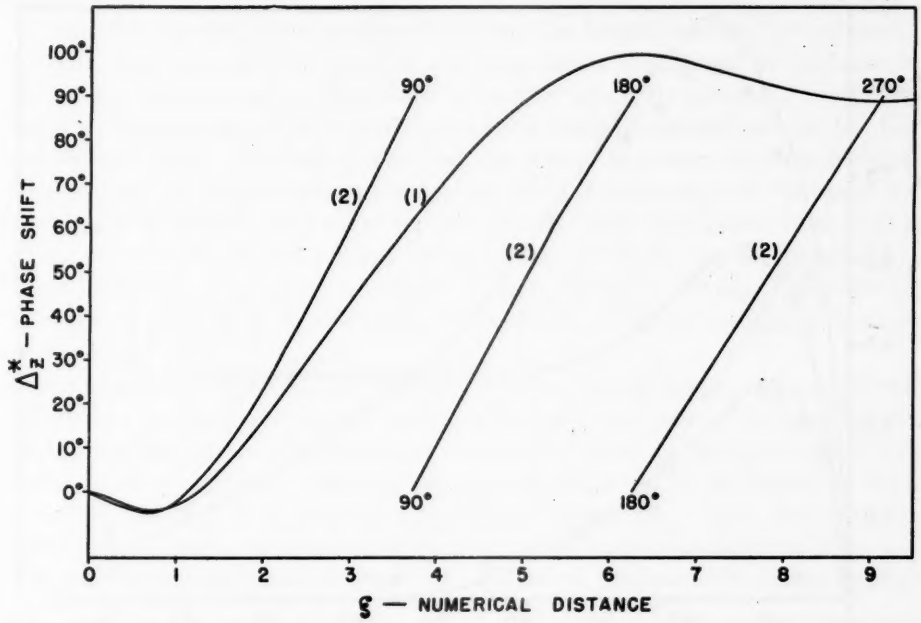

FIG. 5. Phase shifts, Δ_z^*, for magnetic field strength along the boundary and into a conductor as a function of numerical distance, $\xi = 2\pi R/\lambda = R(\omega\mu\sigma/2)^{1/2}$. Angles, θ, between surface and direction of propagation for different curves are: Curve 1, $\theta = 0°$; Curve 2, $\theta = 10°$.

a transmitting loop as a function of frequency. Both loops were small enough (one inch effective diameter) with respect to their separation, five inches, to satisfy dipole conditions quite well. The semi-infinite metallic system was made of aluminum having a conductivity of 2.29×10^7 mhos/meter, corresponding to an earth with $\sigma = .159$ mhos/meter (i.e., $\rho = 6.29$ ohm-meters). Thus, all the quantities for expressing (21c) in terms of receiver voltage are available. In Figure 6 the receiver voltage per unit transmitter current in μ volts/amp (or μ ohms) is plotted, as a function of frequency ($f = \xi^2/\pi\mu\sigma$), directly from Equation (21c). The experimental measurements, indicated by circles, and the different calculated curves are for the various angles into the conductor. It is apparent that the measurements confirm (21c) within 2 percent at all points. As the angle increases, the voltage decreases in general. However, it is more nearly correct to say that the transmission approaches that in an infinite conducting medium. In Figure 7, the transmission vertically downward from the surface of a semi-infinite medium (i.e. $\theta = 90°$, $g = 1$) is compared with similar transmission in an infinite medium. Again the experimental confirmation is shown by the circled points. More complete details of this metallic model will be published in a subsequent paper. It should be remarked here that a dimension is infinite in the model when additional metal cannot be detected experimentally.

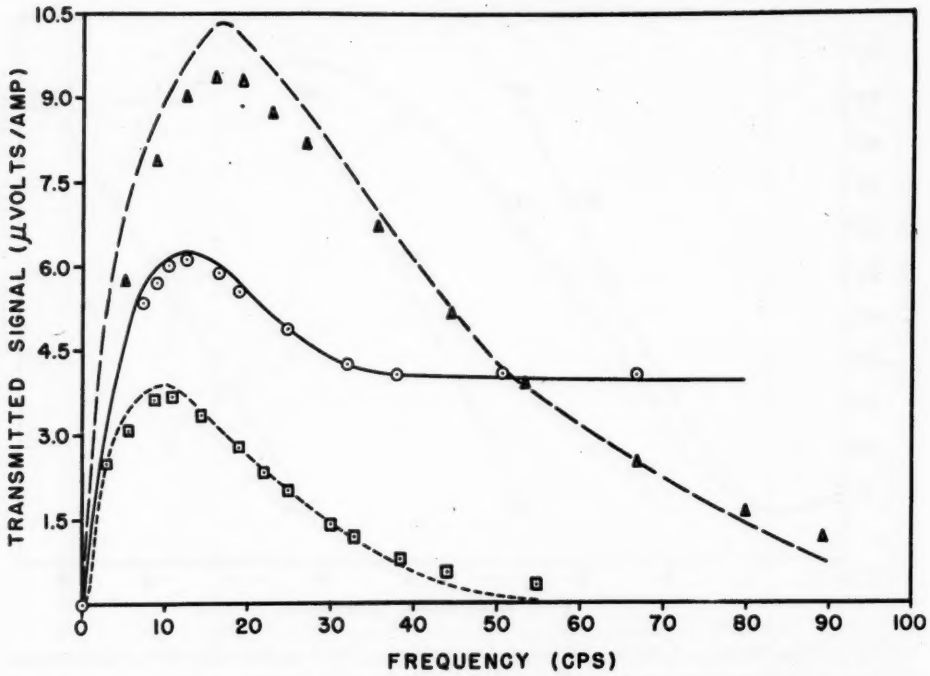

FIG. 6. Transmission along the surface of and for various angles into an aluminum conductor ($\sigma = 2.29 \times 10^7$ mhos/meter). Transmitter-receiver separation = 5 inches. Angle into conductor, θ, for various sets of data are: ⊙, $\theta = 0°$; ⊡, $\theta = 10°$; △, $\theta = 25°44'$. The solid curves are theoretical values taken from Figure 4 with proper normalization factors.

V. CONCLUSIONS

The complete electromagnetic theory for a transmitter and a receiver on the surface of a semi-infinite conductor has been reduced to a form suitable for interpreting any ac electrical prospecting method. The important assumptions necessary are that the displacement currents are negligible in both media. This limits the frequencies to less than 20 kilocycles per second for most sedimentary rocks. For such frequencies, the wavelengths in air are greater than 15 kilometers and can therefore be treated as infinite (i.e., ϵ (air) can be assumed = 0) with respect to the usual distances separating transmitter and receiver. Thus, the geophysical applications of this general theory cover a range of frequencies requiring a different detailed treatment than is required in the radio frequency case, where most of the detailed checks of the theory have been made. In fact, the rf studies have been confined to distances greater than a few air-wavelengths. Because of the big difference in conductivities of materials, these two studies leave a gap in which no detailed work has been done. This gap pertains to distances very much larger than the conductor wavelength, but of the order of the air-wavelength. Of course, in this region the attenuation within the conductor would be much too large for any geophysical applications.

In connection with this manner of viewing the larger problem, it is interesting to note than an apparent paradox noted by Lewis (1946) can be clarified He quotes the results based on an infinite conductor which are obviously in disagreement with the results of Wolf (1946) as well as those presented here, so that both cannot be correct. He then argues that the former is correct because the latter implies that one field component is "independent of frequency" or "in phase with the dipole oscillator." But these statements are simply equivalent to an infinite phase velocity in air, and are not implied from the results but are implicitly assumed when one sets ϵ (air) = 0. Hence, no paradox exists as long as the solutions are applied only when the distances involved are very short compared to an air-wavelength.

In addition to these results for a semi-infinite, homogeneous conductor (herein referred to as a boundary wave), some approximate methods for treating resistive discontinuities within the earth are required in order to interpret geophysical data. In all dc methods, this is attempted by means of image theory in which each discontinuity is replaced by a series of images of the source. Since the only measurement that can be made in such dc work represents the sum of all such images, the interpretation is generally ambiguous. However, the image approxi-

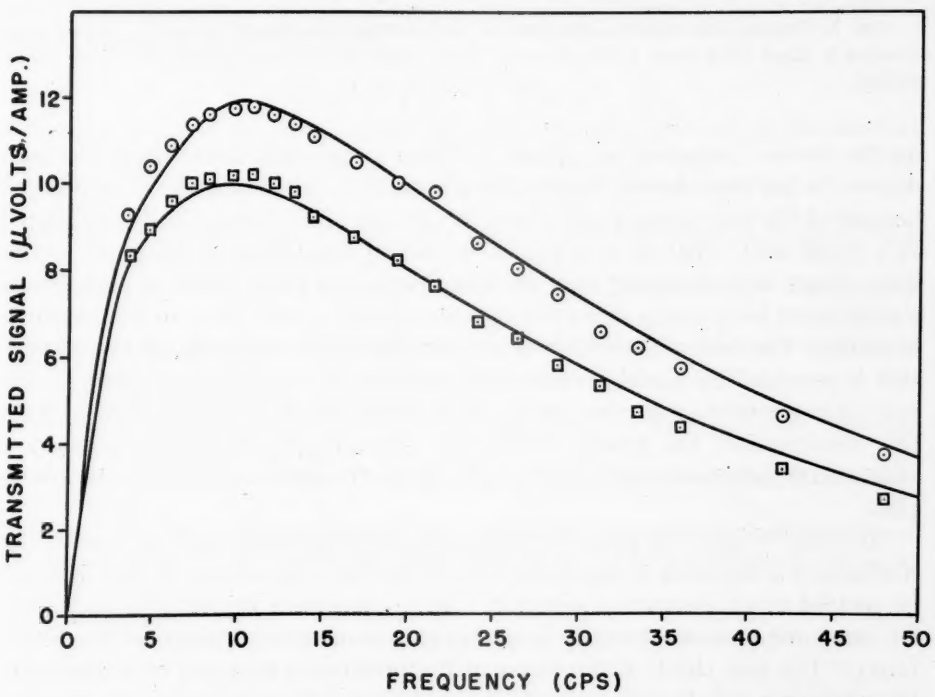

FIG. 7. Comparison between transmission vertically into a conductor from a magnetic dipole on the surface and transmission within an infinite conductor. Solid curves are computed for a distance of 3.8 inches into aluminum ($\sigma = 2.29 \times 10^7$ mhos/meter). Measured values: ⊙ = vertical transmission from boundary; ⊡ = transmission in an infinite medium.

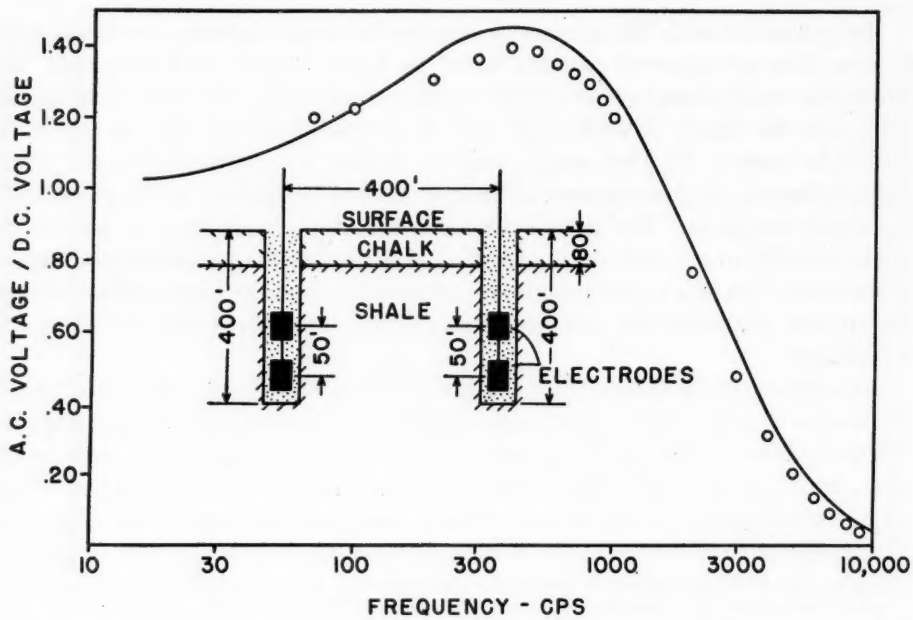

FIG. 8. Transmission within a homogeneous conductor as a function of frequency. ○ values are obtained in Eagle Ford shale, Dallas County, Texas. Solid curve computed from theory of infinite medium.

mation for low frequency ac signals considers image oscillators within the conductor. As has been shown, these produce signals at the surface which are delayed because of the finite propagation time. In the case of sine waves, this is measured as a phase shift, whereas with pulses the actual time delay is measured. It has been shown here, however, that the amplitudes and phase shifts of such image signals must be properly corrected to take account of the effect of the air-earth boundary. The best confirmation of the validity of this entire image approximation is provided by model studies to be reported in a subsequent paper in this journal in which the reflections caused by resistive interfaces will be shown. With this confirmation, the general theoretical approach presented here provides a satisfactory method for interpreting measurements made in geophysical exploration.

In order to make the present scheme generally applicable to all ac prospecting methods, it is desirable to know whether the sedimentary section of the earth can be treated as an electrical conductor. Can displacement currents be neglected? Or, must one assume extremely large dielectric constants, as suggested by Evjen (1943)? The best check of this phase of the problem is provided experimentally by measuring directly transmitted signals within a typical conducting medium The results of such a test are illustrated in Figure 8. A transmitter and receiver were placed in the center of the Eagle Ford shale section near Dallas. The received

signals for various frequencies from zero to 20 kilocycles per second are indicated by circles. The theoretical transmission curve for a homogeneous conductor having the conductivity of the Eagle Ford shale is indicated by the solid line in Figure 8. The agreement shown indicates that no serious error is present in this basic assumption.

Finally, since the distance involved in this test was only 400 feet, it is apparent that the high frequency signals are attenuated too much to be useful in prospecting for structures at depths greater than 1,000 feet. In fact, the attenuation as calculated from simple plane-wave theory must yield the correct order of magnitude in a stratum of known conductivity. Otherwise, the agreement illustrated in Figures 3 and 8 (and supported by many similar tests) could not have been obtained.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Drs. D. H. Clewell and E. V. Somers for helping in the preparation of the manuscript of this paper; to Mrs. C. D. McClure and Mr. John Henkel for performing the computations contained herein; to Mr. A. R. Orsinger for the experimental data in Figures 6 and 7; to Messrs. G. C. Summers and J. K. Godbey for the experimental data in Figure 8; and to the management of the Magnolia Petroleum Company for permission to submit this paper for publication.

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MULTIPLE REFLECTIONS ON THE EDWARDS PLATEAU*

THOS. C. POULTER† AND LEONARD V. LOMBARDI†

ABSTRACT

Seismic records obtained at the same point with hole and surface charges are compared. Evidence is presented that multiple reflections from within the Edwards limestone are sufficiently prominent on the hole shot records to mask and obscure primary reflections. It is postulated that the large number of these multiples is attributable to the great amount of high frequency energy generated in the competent Edwards limestone by a hole shot.

The relative lack of multiple reflections on the Poulter Method records is believed to be due largely to the fact that essentially all of the energy entering the ground is of low frequency in the part of the spectrum available for deep reflections. This nullifies the apparent high frequency selectivity effect of the Edwards limestone.

INTRODUCTION

The Stanford Research Institute has had experimental seismic crews operating on the Edwards Plateau for a total of approximately two crew years. The work is still proceeding; this paper touches on one facet of the earlier research. The work herein described was sponsored in part by the Institute of Inventive Research, of San Antonio, Texas.

The Edwards Plateau is a large area in West Texas in which the Lower Cretaceous Edwards limestone crops out; the immediate area under consideration, in northeast Crockett County, is indicated in Figure 1. The region is underlain by several producing horizons, the most important of which is the Cambro-Ordovician Ellenburger. The Plateau area includes several producing fields, and favorable structural and stratigraphic conditions indicate the probable presence of many more traps. Unfortunately, however, the Edwards Plateau is a notorious "no record" area for the reflection seismograph using hole shots. There are many reasons for the masking of meaningful energies on hole shot records; one of these reasons, the presence of pronounced apparent multiple reflections within the Edwards, was clearly illustrated in the course of some of the experimental work conducted in 1950.

The Edwards is jointed, blocky, and, in places, cavernous near the surface. The net result of this, plus erratic weathering variations, is the arrival of reflected energy at geophone stations a few feet apart with considerable phase or time differences. Horizontal energies are prominent among the contributors to background noise, in some cases obliterating all other energies on parts of the record.

The effects of these factors on the records may be reduced, though not elim-

* Presented at the St. Louis meeting of the Society April 23, 1951. Manuscript received by the editor September 28, 1951.

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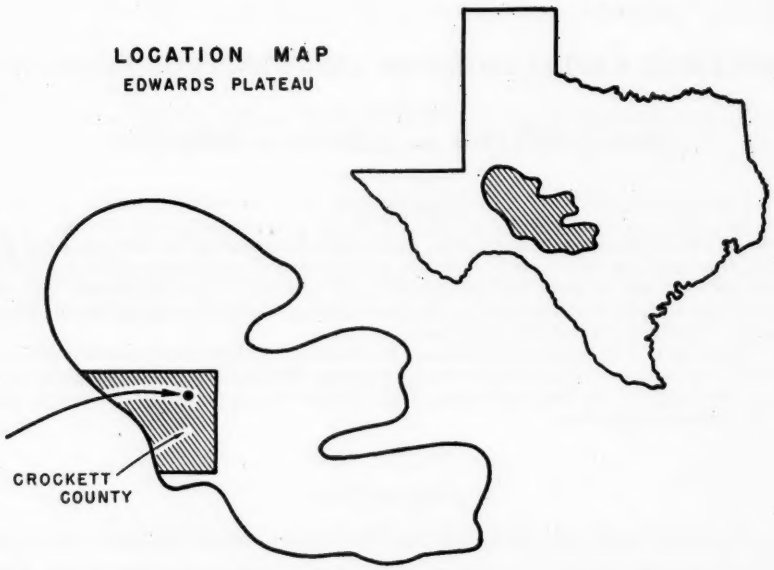

FIG. 1. Location map, Edwards Plateau, Texas. The large arrow indicates the immediate area discussed in this paper (modified after Gillin and Alcock).

inated, by the use of multiple geophone patterns plus various types of mixing. This is a rather large subject on which the evidence is not yet complete. Further discussion will be deferred to a future paper, but patterns of nine geophones per trace and a rather strong (50 percent) taper mix were used in obtaining the records on which this paper is based.

NORMAL HOLE SHOT

It was desired to get a comparison of Poulter Method and various types of hole shot records recorded on split spreads at the same shot point. It soon became apparent that the hole shot records were considerably higher in frequency than the air shot records and plainly contained more events. On closer examination of the hole shot records it was noted that there were three separate sets of events repeating at an interval of 195 milliseconds, with a phase reversal each cycle (Figs. 2b and 3b).

If the repetitive events are to be explained as a series of multiple reflections, the time path between the reflecting planes is clearly short. The thickness of the Edwards in this area is of the order of 850 feet, giving an average velocity of about 8,500 feet per second if the interval of 195 milliseconds represents the two-way time from the surface to a horizon at or near the base of the Edwards. This figure is in fairly good agreement with the shallow Edwards velocity of 8800 feet per second obtained from velocity surveys in the immediate area. The hole shot charges were detonated at a depth of 220 feet. As there are two possible initial reflectors, there should be two sets of multiples, as indicated by the paths shown

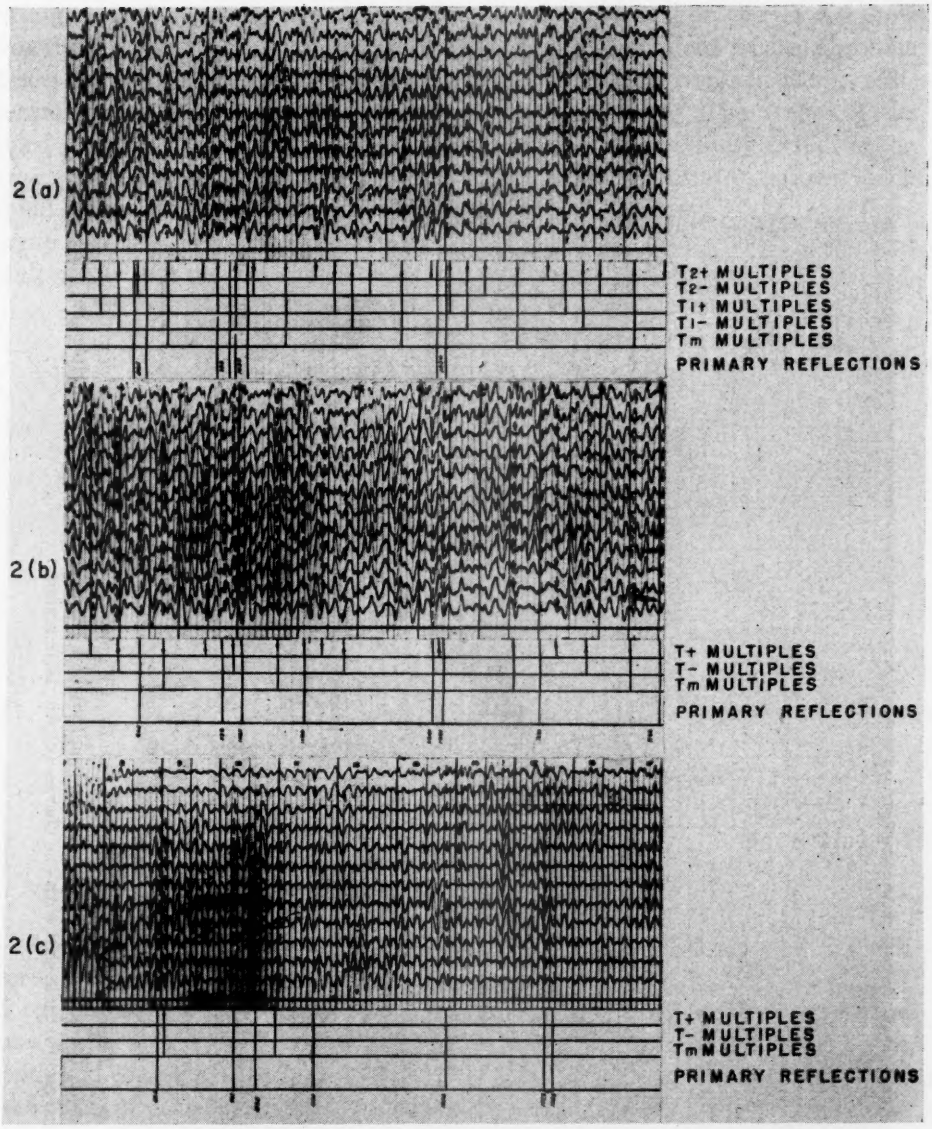

FIG. 2. Portions from 0.7 to 1.7 seconds of records of: (a) Hole shot with two charges. (b) Hole shot with one charge. (c) Air pattern shot. The times given for primary reflections have been checked with a continuous reflection survey and with well data in the area. The multiples marked $T-$ are those initially reflected at the upper interface; those marked T+ were initially reflected at the lower interface (see Fig. 4). The numbers 1 and 2 on the two-charge record refer respectively to the upper and lower charges. The apparent multiples marked Tm occur at the average of the $T+$ and $T-$ times and thus are independent of shot depth. The arrow under each arrival indicates the direction of galvanometer deflection and therefore the phase of the arrival.

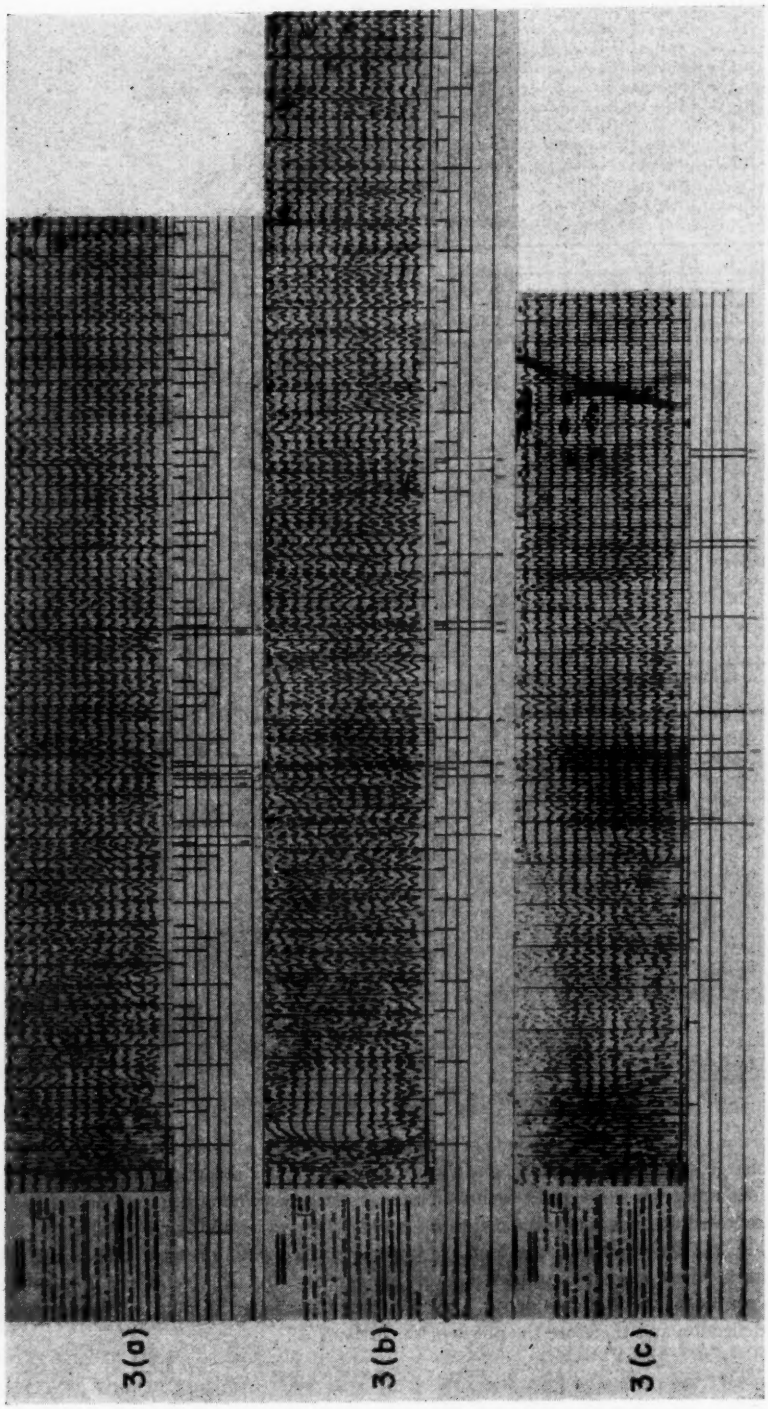

FIG. 3. These full length views of the records of Figure 2 show the large number of multiple reflections on the hole shot records and the resultant high-frequency appearance. (a) Hole shot with two charges. (b) Hole shot with one charge. (c) Air pattern shot.

in Figure 4. Two of the sets of repetitive events recognized on this record show exactly the relative time difference calculated for the different paths. The time associated with any event in these two sets is an integral number of 195-millisecond cycles plus the shot-position-to-first-reflector time. (The events of the third set have puzzling intermediate times.) Finally, the geologic section in the area, as interpreted from well logs, shows a dearth of other formations which could act as primary or multiple reflectors at the time indicated. All of these facts argue that the repetitive events observed on these hole shot records are indeed multiples within the Edwards.

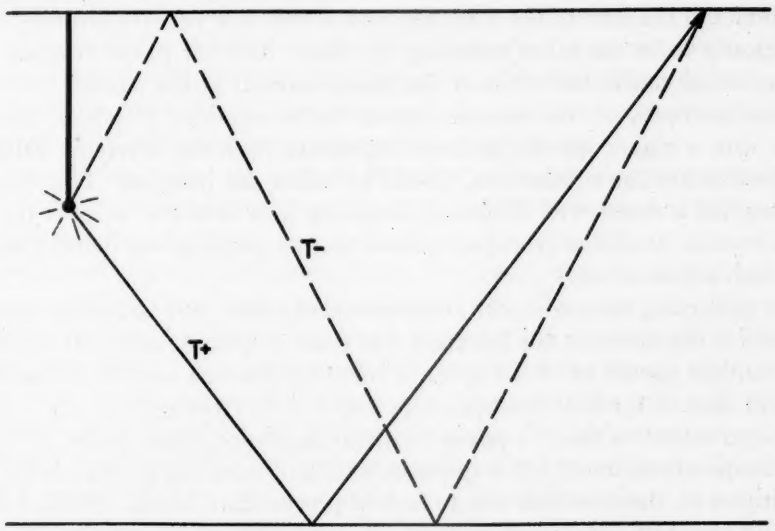

FIG. 4. Diagram of the two possible paths of hole shot energies multiply reflected within the Edwards limestone.

Another record was made with the shot at a depth of 317 feet. Again there were three sets of repetitive events on the record, each having the same interval of 195 milliseconds. Two of the sets of events were shifted with respect to the time origin by the amount predicted because of the 100-foot change of charge depth and consequent changes in the shot-to-first-reflector times. The third set of events, marked *Tm* in Figure 2, remained in the same position. The arrival time of any one of this latter set of events is $(2_n-1)/2$ 195 millisecond cycles, where n is an integer. These are the times that would result from a multiply reflected event originating at the lower reflecting horizon at the shot moment. No logical explanation for this set of events has been found, though the set is present to some degree on all of the records obtained at this shot point.

The existence of multiple reflections is certainly well established.[1] In spite of the evidence stated above, however, it is difficult to see how the energy, after so

[1] E.g., *Geophysics, XIII*, No. 1, Jan. 1948.

many reflections, could remain sufficiently strong to be picked up and recorded, even granting that the later multiples are indistinct on the records and perhaps doubtful.

ENERGY CONSIDERATIONS

The thin weathering probably implies a free surface reflection at the top of the Edwards. The relative specific acoustic resistance at the Edwards-air interface is obviously extremely low, and essentially all of the incident energy will be reflected, the reflected energy being opposite in phase to the incident. That is, the "reflection coefficient" is essentially -1.00.

A contact of the base of the Edwards with a very low velocity stratum would seem logically to be the other reflecting interface. Another phase reversal here, however, would cancel the effect of the phase reversal at the surface. Actually, successive multiples on the records appear to be opposite in phase. Hence a medium with a higher specific acoustic impedance than the overlying Edwards, which itself is low for a limestone, should be below the interface. This could be something like a dense, well indurated limestone lens or bed at or near the base of the Edwards. Available geologic evidence neither confirms nor denies the presence of such a lens or bed.

Even neglecting inverse square and absorption losses, and assuming favorable constants for the media at the interface, the trace amplitude associated with the eighth multiple should be of the order of three-hundredths to four-tenths of one percent of that of the first multiple. (An energy reflection ratio in the range of 0.10 to 0.20 raised to the $7/2$ power; vertical incidence, plane wave, and semi-infinite media are assumed.) It is impossible to determine the amplitude ratios of the multiples on these records due to lack of precise data on the effective db expansion of the AVC. However, it does not seem probable, on the basis of this calculation, that multiples as far out as the eighth would retain recordable energy unless the initial energy were extremely large.

Despite this very small calculated energy return for the later multiples, there are weak events far out on the records at the time positions and with the phases predicted by the multiple reflection hypothesis.

HOLE SHOT WITH TWO SEPARATED CHARGES

There is one more check on these events: a further set of records was shot with two charges suspended in the hole, at depths of 137 and 317 feet, and detonated simultaneously. These records are considerably higher in frequency than the single hole shot records. The same time portion of three records appears in Figures 2 and 3, showing the increase in frequency from air charge to single hole charge to double hole charge. This higher frequency exists throughout the record.

It is obvious that if one hole charge gives two sets of multiples, the double hole charge should give four sets of multiples. The addition of the odd apparent multiples marked "*Tm*" makes the number of sets of multiples three and five, respectively. These five sets are indeed present and are marked on the record.

This particular record shows evidence of the presence of something like sixty multiple reflections among the five separate sets. Clearly here even more than with the single hole charge these multiples, superposed on primary reflections and random and offside energies, result in a very high frequency record on which the primary reflections cannot be located without further evidence. It is, of course, possible that near-surface disturbances accompanying each surface arrival of multiply reflected energy contribute to this increase in frequency.

COMPARISON OF SURFACE TO HOLE SHOTS

Finally, the record of an air shot, using the optimum Poulter Method pattern for this area, was examined for multiples. This record is reproduced in Figures 2c and 3c. There should obviously be considerably fewer multiple reflections, as firing the charge above the surface automatically cuts the number of possible multiples in half by permitting only one set of multiple paths.

It was thought that the vertical directivity of air charge patterns might tend to favor multiples in a split spread. In the Edwards, 85 percent of the energy from an air charge is concentrated in a 30-degree vertical cone.[2]

In spite of this expected effect of the directivity, only seven multiples appear to be present on this record, including again the "*Tm* multiple." The rapid attenuation of these multiple reflections is probably not too surprising. The energy entering the ground is a fraction of one percent of the energy initiated in the ground by the detonation of a hole charge of similar size, although the energy returned from deep reflections is about the same. Probably more important, the frequency distribution of the energy entering the ground from this air charge pattern is peaked at 60 and 40 cycles; the bulk of the energy from a shot hole charge is of much higher frequency. In fact, the energy 300 feet from a hole shot after detonation of a similar sized charge is peaked at about 600 cycles (Fig. 5). It seems probable that a competent limestone like the Edwards may transmit comparatively high frequencies with much less rapid attenuation than most formations.

It may be, therefore, that the enormous amounts of high frequency energy from hole shots are available for multiple reflections when the shot is fired in a formation like the Edwards, even though energy of these frequencies would normally, in what might be termed lower frequency beds, be attenuated and scattered so rapidly as to be of negligible effect a few hundred feet from the shot. A further possibility along the same line is that the reflecting bed near the base of the Edwards is of such dimensions that the higher frequencies are selectively reflected. It is possible to make these multiples more prominent by changing the filtering to admit a larger percentage of high frequencies. Unfortunately, they cannot be eliminated by peaking the filter at a lower frequency without selecting a frequency so low that primary reflections are not recorded.

[2] Thos. C. Poulter, "The Poulter Seismic Method of Geophysical Exploration," *Geophysics, XV*, No. 2 (April 1950), 181–207.

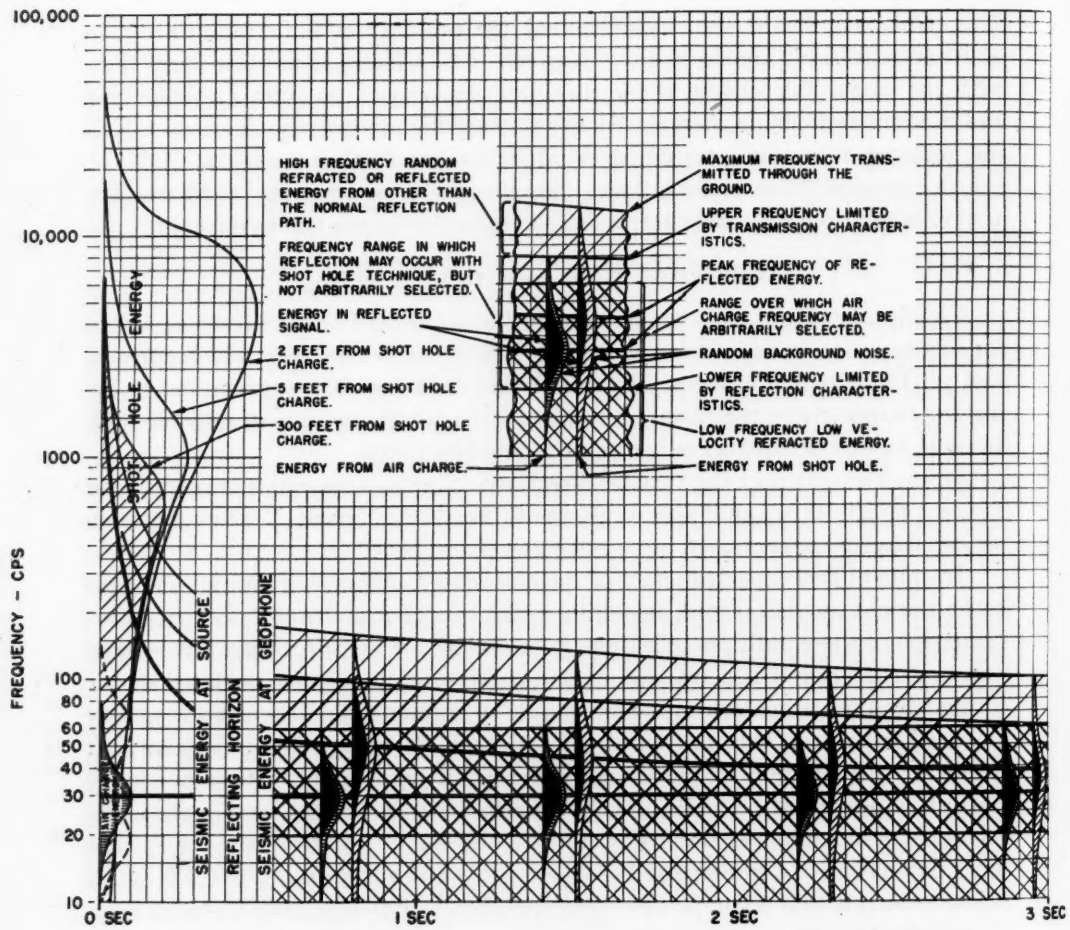

FIG. 5. Frequency distribution of hole and air shot energies at various distances from the source. Reprinted from Thos. C. Poulter, "The Poulter Seismic Method of Geophysical Exploration," *Geophysics, XV*, No. 2 (April 1950), 184.

Another puzzling fact is that the substitution of a large single air charge for a pattern of charges results in the appearance of a somewhat larger number of multiple reflections on the record. The only ready explanation for this increase is that the frequency of energy from a large single charge is peaked considerably higher than that from a normal pattern of charges. Perhaps this greater content of high frequency energy makes more energy available for multiple reflections without increasing the energy available for reflections from below the Edwards.

CONCLUSIONS

This paper neither assumes nor attempts to answer all of the questions connected with the presence of multiple reflections in the Edwards limestone. Hole

shot records contain many more events than can be accounted for as primary reflections. Evidence is presented that many of these events are multiple reflections within the Edwards. These multiples are apparently present to such an extent that their superposition on random and reflected energies creates a high-frequency record on which the desired reflections are generally masked. Apparently later cycles of these multiples are recorded than would be expected according to approximate energy calculations. It is suggested that relatively good transmission of the abundant high-frequency energy available from hole shots in the Edwards limestone may provide an explanation of this large number of multiples. One anomalous set of multiples appearing on all records, and apparently independent of charge position, was noted but no explanation is given.

The multiple reflections in the Edwards are greatly reduced by the use of air charge patterns. The known directivity of these patterns has less effect in producing multiples on a split recording spread than would be expected. It is suggested that the lower frequency of the energy entering the ground, eliminating the very large undesirable high-frequency components of hole shot energy, is the explanation of the lack of multiples and a partial explanation of the higher signal-to-noise ratio obtained with air charges.

Although the Edwards limestone is a special case of a competent material at the surface, an obvious implication of the results herein described is that multiple reflections may be an important component of the undesirable background energy in other areas, although they would not be as clearly recognizable as those within the Edwards.

ON THE RELATIONSHIP BETWEEN SEISMIC AMPLITUDE AND CHARGE OF EXPLOSIVE FIRED IN ROUTINE BLASTING OPERATIONS*

G. M. HABBERJAM† AND JOHN T. WHETTON†

ABSTRACT

An account is given of an investigation into the relationship between charge of explosive fired and seismic amplitude in routine quarry blasting. By keeping the instrument fixed over the investigation and by choosing a suitable recording position the effects of site factor can be considered to have been reduced to a practical minimum.

The observations, which were made at distances of approximately 400 feet, give a relation between first peak amplitude and charge of the type,

$$C = Q \cdot A^{1.242}$$

where the factor Q varied between 1 and 3 approximately and would apparently be assignable to varying blasting conditions.

The results have also been reviewed in the light of an amplitude square relation modified on the supposition that the energy loss involved in practical blasting is a function of the charge.

The relationship between seismic amplitude and magnitude of charge is one of prime importance in any study of quarry blasting vibrations since it forms the basis of any systematic investigation.

It might be expected that, in ideal circumstances, the amplitude of earth movement would be proportional to the square root of energy released in the explosion, or assuming this latter to be in direct proportion to the charge of explosive fired, that a relation of the type

$$\text{Charge} \propto \text{Amplitude squared} \qquad (1)$$

would result.

Such an ideal relation need not necessarily be expected to hold in practical blasting where a certain proportion of the energy developed will be lost in fracturing the rock in which the charge is confined.

A certain amount of confirmatory evidence exists for the above simple type of relation. For very small charges, up to 2.8 kilos, fired in sand, Rixman[1] obtained results of a confirmatory nature, although there appears to be an energy loss incurred in firing in dry, as opposed to moist, sand. Thoenen and Windes[2] in recording blasts made in a mine on the same rock stratum, obtained the relation,

$$A = 0.027 C^{1/2}/d \qquad (2)$$

where A is the maximum ground amplitude in inches, C is the weight of explosive in pounds, and d the distance in feet.

* Manuscript received by the Editor June 6, 1951.

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The above formula applies to the following ranges:

$$20 \text{ lb} < C < 200 \text{ lb}$$

$$300 \text{ ft} < d < 1{,}500 \text{ ft}$$

More recently Morris[3] has stated that a similar type of relation holds in normal commercial blasting if the constant 0.027 be replaced by a "site factor" where the latter is dependent upon the location both of the blast and recording positions.

The observations above made by Rixman and by Thoenen and Windes represent rather specialised tests and it should perhaps be added that the latter investigators, in carrying out surface recordings in a similar range of charges and amplitudes to those of Rixman, obtained a very different type of relation.

$$\text{viz.,} \quad A = Ke^{0.371C} \tag{3}$$

where K is a constant.

From a wide survey of quarry blasting vibrations Thoenen and Windes evolved an equation of the type given below:

$$A = PC^{2/3}(0.07e^{-0.00143d} + 0.001)/100 \tag{4}$$

where A, C and d are the maximum amplitude, weight of charge, and distance in the same units as above.

The factor P performs a similar function to Morris' site factor quoted above and was attributed by these authors to the thickness and nature of the overburden at the recording site. The factor is extremely variable and ranges from a value of 3 on abnormal overburden to a value of 0.1 on bedrock.

From this it will be clear that the bulk of the observations made by Thoenen and Windes are in disagreement with the findings of Rixman and Morris.

Nor is disagreement confined to charge amplitude relations since it will be seen from comparison of equations (2) and (4) that different types of relation between amplitude and distance may be assumed to hold.

The form of seismograms obtained from quarry blasts are generally complicated, although the approximations to simple or damped harmonic wave trains have proved useful in certain circumstances, the former being used by Thoenen

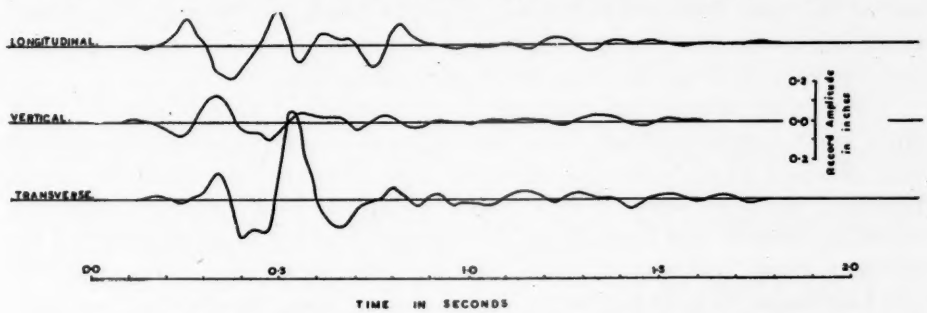

FIG. 1. Seismograms of 11,000 lb blast at one-half mile.

and Windes to get rough figures of the acceleration developed and the latter by Morris in developing the theory of delayed action detonators.

A typical form of seismogram is shown in Figure 1. This seismogram was obtained using a seismograph which records amplitude of the earth movement in three mutually perpendicular directions and has a natural period of about 1 second. By orientating the seismograph in the direction of the blast these three directions correspond to the longitudinal, vertical, and traverse components of the vibration. (See Fig. 2.) The recording is actually that made from a blast of 11,130 lbs of explosive recorded at a distance of one-half mile.

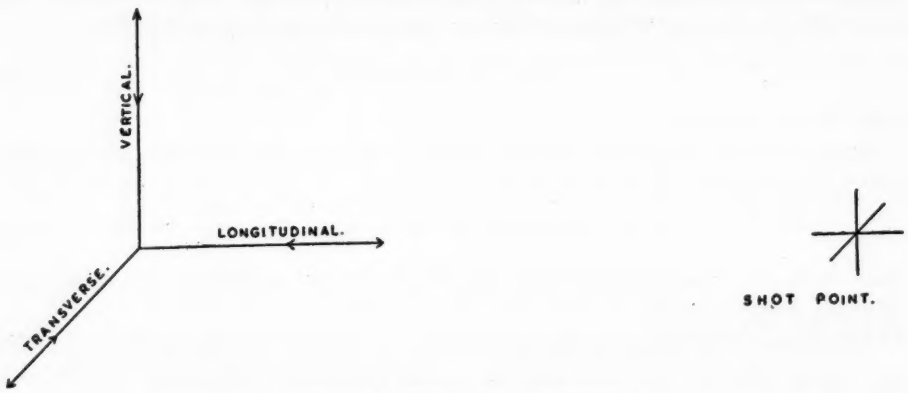

FIG. 2. Orientation of the seismograph.

It will be seen that on this particular seismogram the maximum amplitude recorded occurs on the transverse trace. This particular feature is not a general characteristic although of considerable interest.

Maximum amplitudes generally arise on the longitudinal component but are not necessarily to be associated with the first peak amplitudes, which would be inferred if the motion could be described as of a damped harmonic nature. This does not necessarily detract from the utility of such an assumption in certain theoretical treatments and generally applies in some crude fashion to the latter part of the trace. Referring to Figure 1 it will be noted that the maximum record amplitude on the longitudinal component occurs at the second peak and after that decays in an irregular but generally damped fashion.

Considering seismogram character in more detail at once produces a very much more complex problem. Leet[4] has sought to associate the records obtained with different wave types and claims to have observed compressional, shear, Rayleigh, and Love waves in recordings of an atomic bomb explosion where the recording distance was favorable to the separation of the times of arrival of the different waves, and also in quarry blasting vibrations. From these recordings also Leet claims to have isolated two further wave types, the so-called "coupled" and "hydrodynamic" waves respectively.

Some such mechanism as the above may be necessary in order to explain the complex three-dimensional character of the ground movement.

The existence of such a mechanism has an important effect in any consideration of the variation of amplitude of ground movement with explosive charge fired, since the geological structure of the ground in the vicinity of the blast will determine the relative times of arrival, at the recording point, of the different wave types, and hence possibilities of destructive interference or reinforcement exist. Besides such possibilities there is also the additional problem of division of energy between the different wave types.

In the investigation to be described attention was focussed on an individual peak of the records obtained and the variation of the amplitude of this peak with charge was observed. This procedure was adopted rather than that of determining the overall maximum amplitude, in order to confine attention to a single wave type.

The investigations were carried out at a quarry site near Leeds (England).

EXPERIMENTAL INVESTIGATIONS

The usual blasting practice at this quarry involved the firing of charges of up to 60 lb of explosive, though occasionally bigger blasts ranged up to 200 lb. These blasts were usually carried out on a series of "benches" in the rock with the shots arranged on one, or adjacent, benches. The shotholes, which were drilled 1½ inches in diameter, were seldom greater than 12 feet deep, and the charge per hole ranged up to three lbs. As a consequence, the bigger blasts entailed the firing of a large number of holes simultaneously, and the electric detonators used were fired in series from the electric lighting mains. This method of firing, however, often resulted in groups of shots failing to fire, so that sometimes a bigger blast became, in fact, two blasts of medium size. As a result of both the order of the blasting employed and the chances of misfires causing reduction of the total amount of explosive per blast, the distribution of recordings made at this quarry tend to be concentrated towards lower charges. Throughout most of the work, the explosive used was Polar Ammon Gelignite "B,"' though in one blast the charge included 35 lbs Black Powder.

The worked stone of the quarry corresponds geologically to the Rough Rock of the Millstone Grit series. From the blasting point of view, the stone varies considerably from point to point in the quarry due to the presence of local fissures in the rock. The effect of such breaks is to present lines of easy fracture in the rock and so help the blast to yield more rock per pound of explosive. The character of the rock varied slightly, but the bedding planes were not well defined. Flagstones and shales lie below the quarry floor but are not worked. At the top of the quarry, the overburden consists of a thin bed of good quality sand sovered with top soil, the whole varying in thickness up to about five feet.

Five initial records were made in different parts of the quarry, and on the basis of these recordings the choice of instrument site for the charge-amplitude

TABLE I

Blast No.	Elevation Ft	Distance Ft	Charge lbs	A_1	A_3	A_{400}
5	30	330	106.5	12	18	10.75
6	20	320	48	4.5	6.5	3.85
7	25	330	61	6.2	9.7	5.55
8	50	375	35	4.2	3.5	4.5
9	50	375	23	2	1	2.12
10	60†	375	38	3	3.2	3.25
11	40	330	42	5	7.5	4.4
12	10	330	19	1	1.7	0.85
13	45–50	330	49	5	8.2	4.7
14	45	320	34.6	5	8	4.55
15	10	330	38.3	5.7	8	4.9
16	60†	340	47	4.2	5.5	4.25
17	30	330	63	6.5	8.5	5.85
18	60†	360	48	4.2	4	4.45
19	50	340	38	4	4	3.9
20	35–40	410	45	4.5	6	5.05
21	50–60	385	59	4	4.2	4.4
22	15–20	410	57	5	6	5.35
26	22	340	20	3.2	4	2.95
27	55	360	20	3	3.5	3.1
28	30–60†	325	88	6	6.5	5.55
29	40	330	19	2.5	3.5	2.3
30	all up	400	52	4.5	3	4.85
31	20	280	14	2	3.7	1.5
32	27	280	7	1.5	4.5	1.15
33	50	340	27	4	5	3.90
34	20	330	4	0.5	0.7	0.45
35	55†	420	56.5	3	1.0	3.55
36	40	430	37	2.7	—	2.65
37	8	340	15	3	4.2	2.6
38	35–50	425	135	11.5	10.7	13.45
39	40–45	420	50	2.7	3	3.2
40	50	400	48	4.5	5	5.05
41	50	400	30	3.2	5	3.65
42	34–50	400	88	7	3.5	7.75
43	35–50	410	70	5.5	5.7	6.26
45	60	400	42	2.5	2.7	2.87
46	40	430	152	8	2.7	9.4
47	40	400	87	8	7.5	8.8
48	37	400	35+90*	6.7	6	7.1
49	27	438	198	11.5	6.5	13.4

† Shots fired wholly, or partly, in the overburden.
* 35 lbs Black Powder.

investigations was made. The observation point chosen was that used in the last of these recordings (No. 5), as it was well situated with respect to the quarry face, which spread fanwise in an approximate arc at a distance of three to four hundred feet from this point. This particular layout meant that the distance correction required to be made to any readings would be reduced to a minimum and it would be possible to use blasts fired in any part of the face in this determination.

The readings taken in this investigation, together with some of the recorded information, is set out in Table I. In this table the record amplitudes, in units of hundredths of an inch, of the first and third peaks recorded on the longitudinal trace are given and are shown as 1 and 3 on record 7 (Fig. 3). These peaks correspond to a movement of the seismograph in the direction of the blast point and in each case the amplitude tabulated corresponds to that measured from the interpolated zero line of the records. This has been adopted since the movement is not sinusoidal.

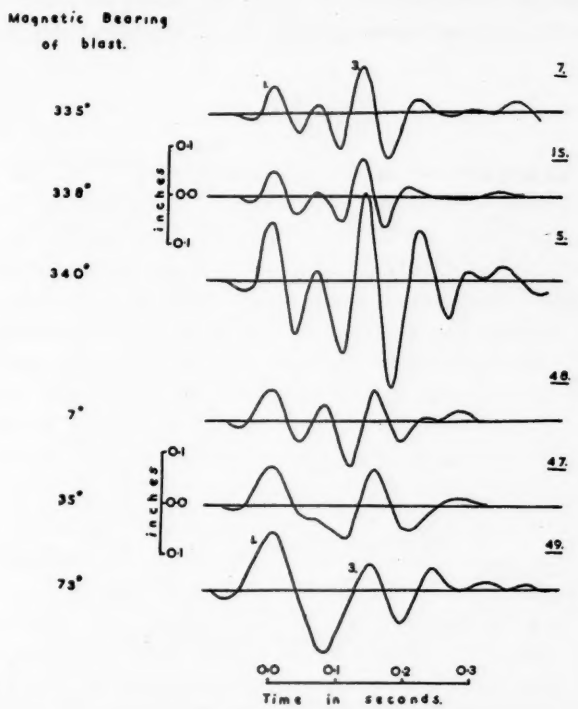

FIG. 3. Change in character of longitudinal records.

In Table I, blast No. 36, only one peak was distinguishable on the record; whilst this is placed as the first peak it might correspond with either the first or third peaks in the other traces.

It is of some interest first to compare the amplitudes A_1 and A_3 tabulated. Out of the 41 records used, 30 readings show the first peak less than the third, one reading, No. 36, was ambiguous, and ten readings gave the first peak amplitude greater than the third.

These conditions suggest that any attempt to relate maximum amplitude with charge from these readings would be of little use. The first peak shown on the longitudinal component is that due to the direct compressional wave from the

blast and this occurs before the arrival of the shear waves on the transverse component. A small movement in phase with the first peak is, however, shown on the vertical component, which is to be expected. This vertical component has been neglected in considering the form of charge-amplitude relations, since it will occur as a small constant trigonometrical factor. By the time of occurrence of the third peak (approx. 0.14 secs later, on records of magnetic bearing 335 degrees) other wave types may be occurring, and hence this peak may be formed from a resultant of more than one movement.

In Figure 3 some of the records obtained on the longitudinal component have been reproduced; the first three records show a general similarity, whilst the

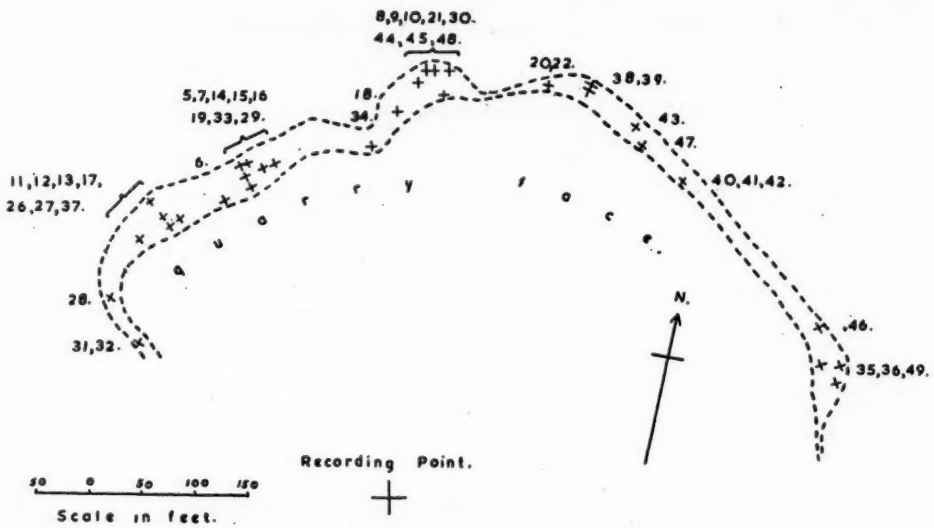

FIG. 4. Positions of observed blasts.

latter show a progressive transformation until a seismogram of the type obtained on record 49 is reached.

This transformation was noted to occur with the change in the orientation of the line joining the observation point to the centre of the blast. The orientation of the blast centre relative to the instruments has been given on the figure with each of the records. This transformation results in a general diminution in the second and third peaks as the blast centres are situated further towards the eastern parts of the quarry face. This suggests that geological factors are entering and that other wave types may be interfering in the trace. For this reason, it was considered better to confine attention to the amplitude of the first peak, that is, the one corresponding to the arrival of the direct compressional wave.

The general layout of records with respect to the quarry face and observation point is given in Figure 4.

Before proceeding further, it is desirable that the readings given in Table I

should be adjusted for distance so that the charge-amplitude values will be represented as if all the readings were taken at the same distance.

If it be assumed that spherical spreading is occurring and that absorption may be neglected to a first approximation over small distances, then we may write:

$$A \propto \frac{1}{d}$$

where A is the amplitude recorded and d is the distance from the blast point.

Further, if within the range of distance variation some standard distance is chosen, the corrected amplitude at this distance is given by,

$$A_c = A \cdot \frac{d}{d_c} \tag{5}$$

where A_c and d_c refer to the corrected amplitude at the distande d_c.

In the corrections applied to the previous amplitude values, the distance "d" from the observation point to blast centre was taken as the sum of the distance "D" as measured along the quarry floor and the height of the blast above this level. Where the total charge fired has consisted of groups at different heights an approximate position for the centre has been taken and used as the mean position. In some cases, where groups were very unevenly balanced, a weighted mean has been adopted. The amplitudes of the first peak corrected to 400 ft are given in the last column of Table I.

These values now require reduction to ground amplitudes. The record amplitudes have first been divided by the magnification of the seismograph and then have been multiplied by a correction factor 'c' to allow for the onset characteristics of the seismograph (H. A. Wilson).[6] See Table II.

The Wilson correction depends for its magnitude on the damped period (1.23 secs) and logarithmic decrement (3.66) of the seismograph and upon the frequency of the impressed motion (in the 10 cps range). Variations in the factor 'c' in Table II indicate slight variations in the character of the onsets of the recorded motion.

Charge Amplitude Relation

The general amplitudes given above are plotted, to logarithmic scales, against the charge fired in Figure 5. The result shows a tendency towards a simple power relationship.

The most probable line through the above points gives the relation,

$$C = 1.95A^{1.242} \quad \text{or approximately,} \quad 2A^{5/4}$$

where C is the explosive charge in lbs and A is the amplitude in units of ten thousandths of an inch.

Transposing this formula

$$A = 0.583C^{0.805}.$$

TABLE II

Record Number	Amplitude in inches	c	Corrected Ground amplitude in inches	(Ground Amp. in inches)$^2 \times 10^8$
5	0.00295	1.07	0.00316	995
6	0.00103	1.07	0.00110	121
7	0.00152	1.07	0.00163	265
8	0.00123	1.07	0.00132	173
9	0.00058	1.07	0.00062	38
10	0.00098	1.07	0.00105	110
11	0.00121	1.06	0.00128	162
12	0.00023	1.06	0.00024	6
13	0.00129	1.08	0.00139	193
14	0.00125	1.06	0.00133	175
15	0.00134	1.06	0.00142	202
16	0.00116	1.06	0.00123	151
17	0.00160	1.06	0.00170	277
18	0.00122	1.06	0.00129	166
19	0.00107	1.07	0.00114	130
20	0.00138	1.08	0.00149	221
21	0.00121	1.07	0.00129	166
22	0.00147	1.08	0.00159	251
26	0.00081	1.06	0.00086	73
27	0.00085	1.07	0.00091	83
28	0.00152	1.08	0.00164	207
29	0.00063	1.06	0.00067	45
30	0.00133	1.10	0.00146	213
31	0.00041	1.06	0.00043	19
32	0.00031	1.06	0.00033	11
33	0.00107	1.08	0.00115	132
34	0.00012	1.07	0.00013	2
35	0.00097	1.07	0.00104	107
36	0.00073	1.10	0.00081	65
37	0.00071	1.07	0.00076	58
38	0.00368	1.10	0.00406	1640
39	0.00088	1.10	0.00097	93
40	0.00138	1.10	0.00152	229
41	0.00100	1.06	0.00106	112
42	0.00212	1.11	0.00231	555
43	0.00171	1.09	0.00186	345
45	0.00079	1.07	0.00085	72
46	0.00258	1.11	0.00288	823
47	0.00241	1.11	0.00268	718
48	0.00195	1.09	0.00212	449
49	0.00367	1.13	0.00416	1720

This relation involves a higher power of the charge fired than in the previous formulae ($\frac{2}{3}$ and $\frac{1}{2}$) although the latter, of course, refer to overall maximum amplitudes.

The distribution of the amplitude values above shows a considerable spread which may be allowed for by varying the multiplying factors in the above relations.

Thus, if one particularly low value at 19 lbs be neglected, the above points conform to a relation of the type

$$C = Q \cdot A^{1.242} \qquad (6)$$

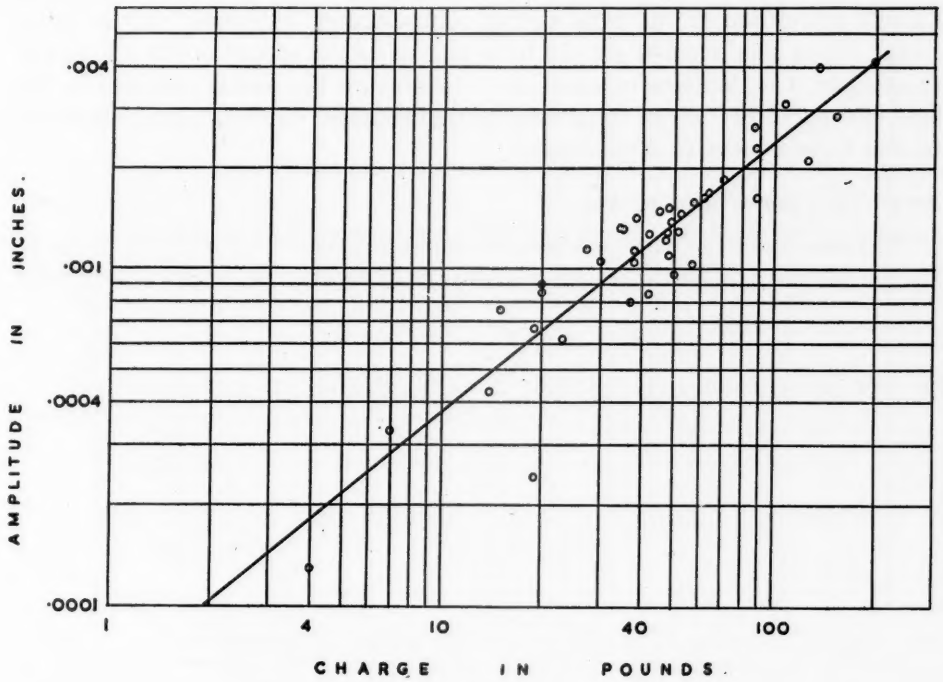

FIG. 5. Relationship of charge and amplitude.

where Q is a factor which varies between the limits 1.26 and 3.16.

The facotr Q, however, cannot in these investigations be regarded as a "site factor" as the recording position was held constant throughout. Minor variations in the state of the recording site with rainfall probably occurred, but since the recording site was close to bedrock (covered only by some six inches of compacted grit) it is doubtful if this could account for the variations observed.

It has already been noted that a variation of seismogram character with direction of the shot to recorder line was observed, but no relation between the spread of 1st peak amplitude values and direction was found.

It appears very much more probable that the factor Q, or at least its major part, is to be assigned to varying blasting conditions and to the energy losses involved.

An attempt was made to explain the spread of points obtained in terms of the particular conditions existing for each blast. A large amount of data on particular blasting conditions was collected, but in this, no single variable showed a predominant tendency to account for the spread. This, however, does not mean that the spread was not due to such conditions but rather that a large number of variables was contributing. Not the least of these is probably the presence of breaks in the rock, previously mentioned, which varied over quite small distances.

The energy developed by an explosion is dissipated in breaking and throwing the rock, as heat, in transmission to the rock, and possibly in other ways; but only

a small proportion of the total energy is propagated as seismic waves. Such energy losses may account for the form as well as the spread of the amplitude values, and it is therefore of some interest to review the results obtained in the light of departures from an amplitude squared relation, which appears to be more tenable from a theoretical standpoint.

Amplitude Squared Relationship

The squares of the corrected ground amplitudes have been given in Table II and are plotted against the weight of explosive in Figure 6. This graph illustrates

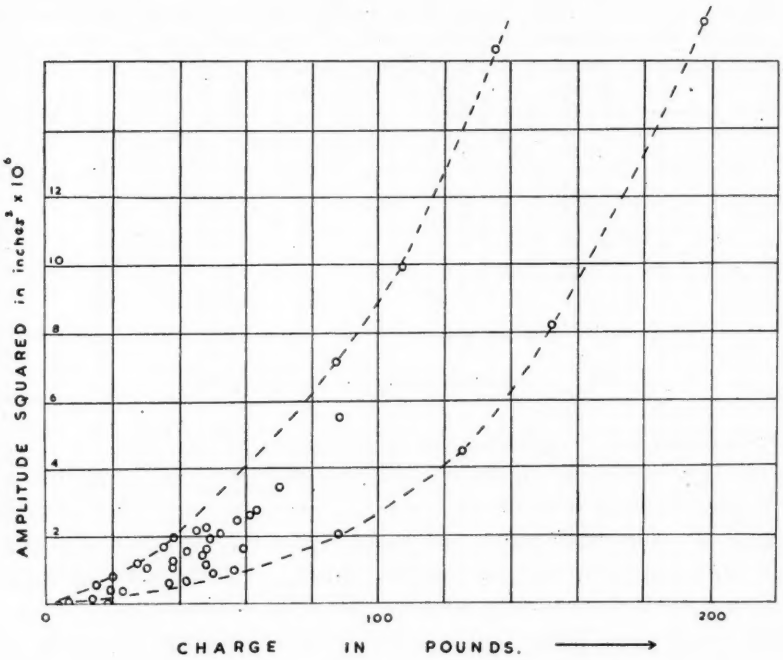

FIG. 6. Amplitude squared relationship.

the general form of the amplitudes obtained, the spread being indicated by the dotted curves on the figure.

Let it be considered that energy losses imply that the effective charge producing the vibrations is decreased by an amount "E," then the modified amplitude squared becomes

$$(C - E) = G \cdot A^2 \tag{7}$$

where G is a constant.

If, now, it is considered that $E \propto C$, then putting $E = m \cdot C$ where m is a constant, the following is given:

$$C(1 - m) = G \cdot A^2$$

or

$$C = G \cdot A^2/(1 - m).$$

Thus a constant proportional energy loss would still give an amplitude squared relationship.

If, however, it be assumed that a relation $E = nC$ exists, where n is now a function of the charge, this gives

$$C = G \cdot A^2/(1 - n) = \gamma \cdot A^2.$$

Further to conform with the observed values it is to be supposed that the proportion n decreases with increased charge so that in the limit $C \rightarrow \infty$

$$n \rightarrow 0 \quad \text{and} \quad \gamma \rightarrow G.$$

Another limitation is imposed by the fact that n cannot be greater than 1.

These conditions are met by a fraction of the type,

$$n = p \cdot e^{-rC},$$

where r is a constant and is positive and p is another constant which is not greater than 1.

The general equation now becomes,

$$C = G \cdot A^2/(1 - p \cdot e^{-rC}). \tag{8}$$

In Figure 7 two curves have been constructed where the particular value of G used has been 0.0463 in both instances, i.e., both curves shown correspond to variations produced in the same amplitude squared relation. Curve 1 refers to the relation obtained when $p = 7/8$ and $r = 0.0047$; and curve 2 to that when $p = 1$ and $r = 0.00183$.

If C is the weight of explosive in lbs, and A is the ground amplitude in units of 1/10,000th inch, then the curves correspond approximately to the limits of the spread of values obtained in Figure 6.

This treatment illustrates the type of modification necessary to reconcile a charge-amplitude squared relation with the observed results. That is, in practical blasting an energy loss is introduced, and this energy loss is such that the proportion of the total charge operative increases as the charge increases. This is also inherent in the empirical power relation given earlier in equation (6), and this latter has considerable advantages in practical convenience as well as conforming more closely to the observed values. This power relation if extrapolated to the region of high charges will however give rise to larger amplitudes than the maxima observed by other investigators, and thus a modified amplitude squared relation may have an applicability over a wider range.

The relation determined above has however been based on an assumed am-

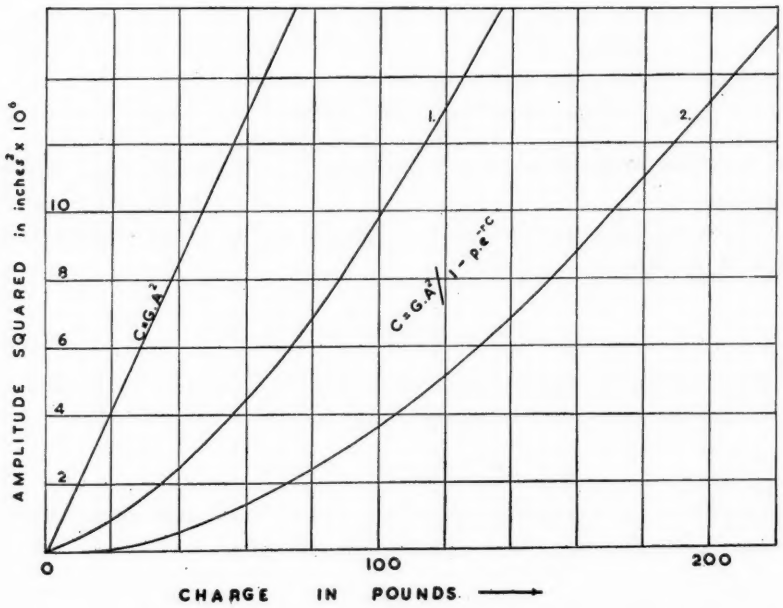

FIG. 7. Curve 1 results from setting $\rho = 7/8$ and $r = 0.0047$; curve 2 results from setting $\rho = 1$ and $r = 0.00183$; compare these with limiting values obtained in Figure 6.

plitude squared law so that both this and the power relationship are purely empirical and may not be applied outside the range considered.

It should also be added that this investigation was concerned with the form of relationship holding and the results may not be applied generally without some consideration of "site factor" which would be expected to enter.

ACKNOWLEDGMENTS

The authors wish to express their thanks to Dr. J. McG. Bruckshaw for helpful advice and criticism and to Colonel E. Tillotson for his interest in the work.

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SOME USES AND ABUSES OF THE SEISMIC METHOD*

B. B. WEATHERBY†

The mid-year meeting of the Society of Exploration Geophysicists is assuming more importance as time goes on, since it is composed to a greater and greater extent of those who are actually on the firing line,—the supervisors, party chiefs, observers, and computers who are directly involved in the operation of more than 500 seismic crews. These are the men on whose shoulders lies the major responsibility for seeing that the work is efficiently conducted. Considerably more than one-half of all the crews are operated by the contracting geophysical companies, so these remarks will be addressed to the men in these organizations as well as to those who are responsible for the operation of company crews.

In its broadest aspect the major problem confronting exploration geophysicists in the United States is to keep this country supplied with the necessary oil and gas. This is a problem of immense proportions. In 1950, for the first time, over one-half of the energy requirements of the American economy were supplied by oil and gas. Recently daily crude oil production rates indicate that more than 2 billion barrels will be produced in 1952. It is difficult to comprehend such an astronomical figure, so an example or two may serve to show how much oil is being used and how much must be found every year.

Western Canada, particularly Alberta, came into the limelight a few years ago because of the discovery of the two large reef oil fields at Redwater and Leduc. More recently a number of smaller fields have been found there as the result of an aggressive exploratory campaign. In spite of the large size of Alberta's known reserves, they add up to about the same amount as the quantity of oil consumed in the United States every six months.

The huge East Texas field, by far the largest found in the United States to date, except perhaps for the comparatively new Spraberry accumulation in West Texas, has produced in over 20 years about the same amount of oil as is needed in a little over a year at our present rate of consumption.

The problem of finding two billion barrels of oil a year is a hard one to solve, since it occurs at a time when oil is becoming increasingly difficult to find. The difficulty is further aggravated by the fact that even greater amounts may be needed in the future. It was stated at the recent A.P.I. meeting in Chicago that world production rates in the next ten years will probably need to be some 35 percent larger. The United States has been producing nearly two-thirds of the world's oil from one-third of the world's petroleum reserves. In mid-1950 the

* Presented at the Dallas Regional Meeting November 19, 1951. Manuscript received by the editor December 27, 1951.

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excess efficient productive capacity in the United States was approximately one million barrels per day, but this has dwindled to about one-half this amount at the present time. Furthermore the state of international affairs may make it necessary to increase producing capacity beyond the figures previously mentioned. There can be no doubt of the immensity of the problem and of its increasing complexity.

In his annual review of wildcat drilling Dr. F. H. Lahee said that of some 4,000 wildcats drilled in 1950 on technical information only one out of eight was successful (1). This low batting average is an index of the difficulty of finding oil, and at the same time it is a measure of the opportunity for improvement. The small size of the accumulations in many discoveries has also been emphasized (2). This suggests that one approach to the problem would be to allocate a larger percentage of exploratory activity to those areas where the density of geophysical coverage and the density of wells is sufficiently low to give a better chance for the discovery of oil fields of substantial proportions.

In the last few years there have been times when there were from 80 to 100 crews in the coastal areas of Texas and Louisiana. There were also quite a number in both the San Joaquin Valley of California and central Oklahoma. These crews were working in counties, parishes, and townships in which there had been sufficient previous shooting to cover the areas thoroughly from 20 to 50 times. It is these programs of some years ago that are responsible for the present day discoveries, since an average lag of some three years exists between the initiation of an exploratory campaign and the discovery of oil as a result of it. In addition to the heavy seismic coverage there was a sufficient density of wells in a good part of these areas virtually to preclude the existence of any very substantial field.

If the emphasis is to be placed on larger discoveries then it will be necessary to curtail activities in these densely shot and densely drilled areas and to move out to the more hazardous but potentially more profitable provinces which are relatively undeveloped. The February, 1951, *Bulletin of the American Association of Petroleum Geologists* lists a substantial number of areas with thick sedimentary columns of marine origin where little prospecting has been carried on. These more or less attractive areas extend from the Florida peninsula on the southeast to Nevada and even Washington on the northwest. Recent developments in the Williston Basin suggest that a new petroliferous province has been found as a result of prospecting in such areas as this. In addition there are a substantial number of relatively small intermontane basins or valleys which have petroliferous possibilities but which have seen little or no exploratory activity. Prospecting in the Cuyama Valley of California resulted in a substantial discovery not too long ago.

However, re-allocation of crews is not the only approach to the solution of the major problem. Another line of attack would be the application of a new prospecting tool, but there is no new method that has demonstrated its ability to make significant contributions to the nation's reserves. The approach to the

problem which is emphasized in these remarks is the more efficient use of existing seismic methods and crews. A considerable part of our exploratory program is being conducted in an intelligent, business-like, and efficient manner by competent and serious-minded men. Nevertheless, considerable improvement in efficiency can be achieved by careful attention to the following points.

Some surprising differences have been observed in the quantity, quality, and unit costs of work performed by different crews in the same area. Usually it is difficult to make an entirely fair comparison because of differences in weather, topography, and surface conditions as well as variation in reflection quality even though the areas of comparison are adjacent to each other. In the comparisons

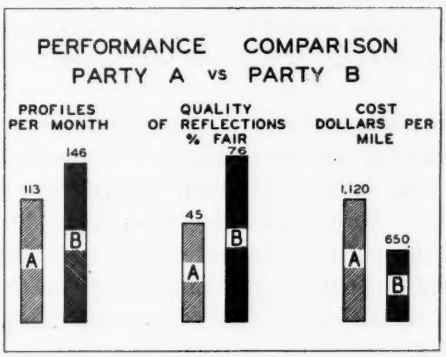

FIG. 1

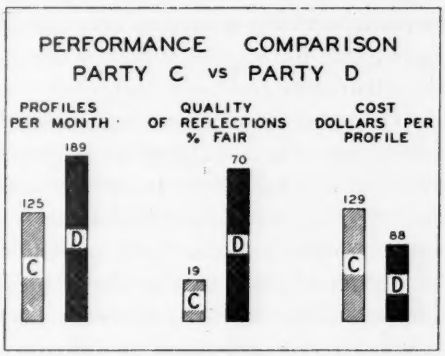

FIG. 2

presented here the time of year and weather conditions were essentially the same and the areas were identical.

Figure 1 shows a comparison in performance between party *A* and party *B*. The bars at the left are scaled to represent the average number of profiles shot per month, 113 for party *A* and 146 for party *B*. The bars in the center indicate that 45 percent of the key reflections on the records of party *A* were graded fair or good, while 76 percent of those on the records of party *B* were graded fair or good by the same standard. The bars at the right show that the unit cost of party *A* was $1,120 per mile compared to $650 per mile for party *B*. On a prospect that took 1½ years to shoot the saving that could have been effected by the use of party *B* rather than party *A* would have been more than $100,000, not to mention the great advantage of the higher quality data.

Figure 2 shows the performance comparison of parties *C* and *D* operating in a different area from the first example, but again under identical conditions. The bars at the left show the average number of profiles per month, 125 for party *C* compared to 189 for party *D*; the bars in the middle show 19 percent of the key reflections were graded fair or good on party *C* compared to 70 percent on party *D*; and the bars at the right indicate the unit cost of party *C* was $129 per profile compared to $88 per profile for party *D*. In this case the difference in reflection

quality was so great that the work of party *C* was repeated to get a dependable map. Additional comparisons of this kind have been made with similar results, but these two examples should suffice to show the wide variations in efficiency that do exist.

It is obvious that the indices which have been used in these comparisons do not give the whole story of the effectiveness of a seismic program. Differences in instruments, differences in instrument operating practice, and variations in field procedure are factors which can influence these indices directly. But the effectiveness of a particular seismic program also depends upon its relationship to its geological setting, on the interpretation of the seismic data, and the integration of the data with other geological information before the final evaluation is made, and these factors may not influence the operating indices which have been cited. Both types of factors are discussed here. The first one to be considered is instruments and their operation.

Over the years seismic instruments have been developed to a high degree of perfection. Their stability is so great that they can withstand continuous mechanical shocks. They can operate under wide variations in temperature and humidity. They have quite flexible electrical characteristics which can be adjusted to meet greatly variable field conditions. Automatic volume controls keep the amplitude of the traces on the record within bounds. The effect of these marked improvements in instruments has been to permit exploration to spread to areas which are increasingly more difficult to work and in which only a few years ago it was not possible to do a satisfactory job. However, there are still some of the older instruments in use which should be retired at the earliest possible moment, especially if one of the more difficult areas is involved. Unfortunately, the advanced state of instrumentation has not reduced the requirement for skilled operators. Since more variables are under his control, more skill is necessary in manipulation of instruments, if the best possible record is to be obtained at each location. Perhaps one of these days the user of a set of seismic instruments will need to know no more about the theory and operation of his instruments than does a paleontologist about the theory of optics, and perhaps the taking of a seismic record will be a simple an operation as bringing a *Heterostegina* foraminifera into focus in a microscope. Until such time the men who are responsible for the operation of the instruments should have considerable training and experience if they are to obtain the best results of which the instruments are capable.

The recording of time breaks, up-hole times, and first breaks should approach the mechanical perfection of focusing a microscope, and although the recording of these events is generally satisfactory there is still room for improvement. Thus in the example given in Figure 1 all of the first breaks on the records of party *A* were poor compared to only 10 percent of those on the records of party *B*. Hence, weathering calculations using first break times would be much more reliable on the data for party *B*, which was the more efficient crew in other respects.

The invention of the automatic volume control (AVC) was at first blush a

great boon to the operator. By its use the number of shots necessary to cover the desired range of reflection depths was greatly reduced. It is a rather common practice for the operator to shoot a sufficiently high charge to cover the entire depth range with one shot. Unfortunately, in so doing it frequently happens that little attention is paid to the depth to basement and the charges generally used are much larger than necessary to reach the maximum depth of interest. Quite aside from the cost, which is not inconsiderable, this over-charging imposes a severe strain on the ability of the AVC to hold amplitudes within bounds in the early part of the record and may well lead to distortion of shallow reflections. An appreciable part of one prospect was covered with charges of from 15 pounds to 20 pounds before a field check indicated that 2 pounds gave adequate amplitude to the depth of granite. In the examples in the figures, the more efficient parties used less than half the average charge shot by the less efficient parties.

Suppression was adopted when the amplitude variations in the early part of the record were too great for the automatic volume control to handle, with consequent distortion of the shallow reflections. But suppression is also used to obscure the amount of ground unrest and instrument noise at the time of the shot. It reduces the magnitude of the first breaks, and in some cases makes them unusable for any weathering calculation. In one instance a substantial amount of work was done before it was discovered that the suppressor became inoperative just in time to allow the previously suppressed noise to interfere with one of the key reflections. In another instance a large part of a prospect was shot with a combination of suppressor and expander which so affected the sensitivity at the time of the key reflection that its amplitude was only a fraction of those on either side of it, whereas it should have been the outstanding reflection on the record. Unfortunately, the true relationship of the various reflection amplitudes was not discovered until fairly late in the program.

Choice of filter settings is now within the discretion of operating personnel. Some operators favor broad band pass characteristics, others a narrow band pass which may be peaked either low or high. It is logical to expect that these characteristics will be chosen so as to favor the key reflection in a particular area. However, it was found in at least one case that the filter setting being used was doing an excellent job of seriously damaging the desired reflection.

Most of the mistakes with regard to instruments and their operation could have been corrected before they reached substantial proportions by a careful and regular check of the instruments made by an operator with sufficient knowledge of their action to be able to spot and correct difficulties as soon as they developed.

After examining the *modus operandi* in a large number of areas it has been observed that there is a striking uniformity in field procedure, regardless of very substantial differences in field and geological conditions. This leads to the conclusion that there is too much standardization of field operations. Furthermore, considerable resistance from operating personnel has been met when efforts were made to adapt the program to conditions in a particular area. While much can

be said for making field operations as routine as possible in order to increase output, it should not be carried to the extreme of interfering appreciably with record quality. This lack of flexibility has caused continuous profiling to be used in areas of excellent reflection quality where spot correlations could have covered the area much more cheaply and with a more uniform density of data. Even in areas where shot holes are expensive and will stand up to repeated shots and where the reflections are not impaired by the wider angles, straddle or split spreads are used, whereas if the full spread was shot from each end the number of holes needed would be approximately halved. Again, there are some areas where hole noises seriously interfere with the near vertical reflections, and others where the reflection quality is appreciably better at the wider angles. In such areas the spread should be moved from its close proximity to the shot point.

This concludes the discussion of instruments and field procedure and leads to consideration of those factors which have a less direct influence on the performance indices but which are very important in determining the effectiveness of a seismic program. The interpretation of seismic data is the first of these.

Spot correlations occasionally resulted in the miscorrelation of so-called reflection character. This has been largely eliminated by continuous profiling. With the use of this latter method care must be exercised not to push the reflection "picks" too far in an effort to establish a non-existent continuity. If the reflection amplitude virtually disappears on a given record, then continuity may disappear too, and the picking of very low amplitudes will only indicate a false continuity on the cross sections which can well lead to erroneous conclusions concerning the geological structure. Where the data are discontinuous and made up of a series of reflections from a zone rather than from a single reflecting horizon, the dip of the beds in that zone is generally shown on the cross section as a so-called "phantom horizon." The dip on this phantom horizon should be of the same magnitude as the dip shown by the separate dip segments and neither increased nor decreased at the whim of the interpreter. If the time ties from profile to profile are in error by more than two- or three-thousandths of a second then every effort should be made to find out the reason and to correct it. If these differences accumulate around a traverse rather than cancel, they may lead to an erroneous interpretation of the structure. Though attention may be focused on a particular reflecting horizon or horizons in a given area, there is likely to be considerable additional information on the record, all of which should be utilized to the extent perhaps of making several different isopach maps. Even in areas where the shallow horizons are supposed to have no particular geological significance they may still give indications of structure which may later turn out to be of great value. For example, a number of West Texas reefs have apparent uplifts in the beds above the reefs.

In shooting over certain faults which are known from well data some unusual events have been observed on the records. These events suggest that occasionally the fault plane itself acts as a reflector and in other cases that some part of the

path of the reflected wave has been along the fault plane. On the one hand these unusual events offer the possibility of recognizing faulting although their correct interpretation may not be easy, while on the other hand the interpretation of the structure adjacent to the fault may be erroneous if the relationship of such events to faults is not recognized.

Substantial changes in velocity sometimes occur in short distances and geophysical maps can be periodically reviewed and perhaps corrected as this information becomes available. Whether a seismic map is expressed in depths or time it is implicit in the geological interpretation that the velocity from point to point is either constant or varying according to some assumed rate. An unexpected change in velocity caused an error of 620 feet in the depth difference between two points 6 miles apart on a Pennsylvanian horizon in West Texas. Every wildcat well gives valuable information, not only on the depths to the different horizons, but also on the stratigraphy and lithology. A restudy of the geophysical maps in the area around each new well may lead to conclusions of importance.

Much has been said about the relation between geology and geophysics and much probably needs to be said in an effort to increase the effectiveness of exploration campaigns. In the writer's opinion there is a fairly definite point at which the responsibility of the geophysicist ends and that of the geologist begins and there should not be too much overlap. However, further comments on this subject are beyond the scope of this paper. Attention is given here only to the relation of surface geology to seismic programs.

A great deal of oil has been found by drilling on surface and near surface structures and this method of prospecting has been rejuvenated by photogeology with some success. As might be expected, some dry holes have been drilled in recent years on Tertiary surface structures in the Rocky Mountain area. Subsequent to drilling the dry hole some of these structures have been shot with the result that no structure was found at depth. This suggests of course that the shooting should have preceded the drilling of the well. There are some surface structures having beautiful exposures of rim rock older than Tertiary that have developed into very substantial oil fields from drilling the surface closure. Examples of this type are Oregon Basin and Elk Basin where the Mesa Verde is on the surface. There are other surface structures that appear to be condemned by drilling. These should be carefully shot to see if the dry holes are on or near the top of deeper structure for there may be considerable asymmetry and a very appreciable shift of structure with depth. Conversely, an absence of structure in these surface beds, even though somewhat older than Tertiary, does not necessarily mean that there is no deeper structure below.

There are considerable areas overlain with badly crumpled and faulted surface beds which may or may not reflect the conditions of the deeper beds. At depth there may be a much simpler configuration of the strata, and consequently such areas are worthy of sufficient exploration to find out the true subsurface conditions.

In conclusion, the principal thesis of these remarks is reiterated—that most of the weaknesses in instrument operation, field procedure, and handling of data are due to inadequately trained personnel. The shortage of trained manpower may be explained by the fact that exploration has expanded more rapidly than men have been trained, but that is no excuse for continuing operations at less than maximum efficiency now. When competent supervisors are prompt in correcting weaknesses that crop up in the field, when party chiefs and observers not only understand the operation of the instruments but also the way to use them to the greatest advantage, when party chiefs and computers are interpreting seismic data accurately and thoroughly because they are aware of all the implications of the data, and when all of these men have been briefed on the geology of the area under investigation, then the general quality of seismic work will improve. Then the challenge of finding two billion barrels of oil a year will be met most effectively and at the greatest profit to exploration geophysicists.

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(1) *Bulletin of the Amer. Assoc. Petrol. Geol.*, Vol. 35, 6 (June, 1951), 1129.
(2) *Op. cit.*, p. 1139.

ERIC UNO GARPNER

MEMORIAL

Erik Uno Garpner, geophysical consultant, died at his home in Los Angeles of a heart attack following a few months' illness on November 25, 1951. He is survived by his widow, Thelma Garpner, and two small sons, Erik Ian, and Jan Alan, of the home address, 4612 Lomita Street, Los Angeles 19, California and his mother and a sister, both of Stockholm, Sweden. His passing is a great loss to his family and a wide circle of close friends in the geophysical industry.

Erik U. Garpner was born August 9, 1901 in Lindesberg, Sweden, the son of a jeweler and watch-maker, Erik Person Garpner, and Emma Peterson Garpner. He received his early education in Sweden. He was imbued early in life with the spirit of geology and mining as the result of the influence of both his grandfathers and two uncles who were mining engineers. Erik came to the United States and entered the Colorado School of Mines at Golden in 1923, and graduated in 1927 with the degree of Engineer of Mines. While at Golden be was elected to membership in Tau Beta Pi and Sigma Gamma Epsilon, honorary engineering and geological fraternities respectively. Aside from Swedish, his native tongue, he spoke and read English, German, French, and Spanish.

After graduating from Colorado School of Mines he paid a short visit to his native land of Sweden. He then returned to America, took out citizenship papers, and accepted a position with the Dixie Oil and Gas Company. He was naturalized an American Citizen on July 15, 1932. When the Dixie firm later became a part of the Stanolind Oil and Gas Company, Erik was transferred to the Tulsa headquarters as geophysicist. During the depression years 1931–34, he was employed by Geophysical Research Corporation, and later re-employed by Stanolind. He married Thelma Dennis at Lake Charles, Louisiana, on September 15, 1934. In May 1942 Erik was made a research engineer for Stanolind and assigned to their research laboratory on North Lewis Avenue in Tulsa. In May 1945, along with several other Stanolind employees, Erik joined the then newly incorporated firm of Frost Gravimetric Surveys, Inc. He later became associated with his old friend and Stanolind co-worker, David E. Reed, as consulting geophysicist for Reed Magnetic Surveys, Tulsa. In the summer of 1950 Erik accepted a position in the newly created department of gravity of Seismograph Service Corporation, Tulsa, to supervise some special work being one by that organization. It was during this employment with S.S.C. that Erik first became ill with high blood pressure. He took a leave of absence in May 1951, and attended the Mayo Clinic of Rochester where his doctors advised him to take six months off to rest in California.

Erik will long be remembered by his many close friends and associates for his indefatigable ability, his keen sense of fair play, and his untiring devotion to his family and profession. He had a tremendous zest for mining geology and geophysics. His methodical approach and the meticulous care with which he so ardently carried out his assignments will not be forgotten by those of us who were fortunate in working with him. He had been a member of the Society of Exploration Geophysicists since 1945.

V. L. (Vic) Jones

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,560,834. S. Whitehead and B. Rosenblum. Iss. 7/17/51. App. 1/24/45 and 1/9/46.

Location of Conducting and/or Magnetic Bodies. An electromagnetic prospecting system using a large energizing loop and several sets of balanced search coils arranged on a frame so that the algebraic sum of the area-turns moments for each set of coils is the same.

GRAVIMETRIC PROSPECTING

U. S. No. 2,559,919. G. V. A. Gustafsson. Iss. 7/10/51. App. 4/3/47 and 4/3/48. Assign. Bolidens Gruvaktiebolag.

Apparatus for Measuring Forces, Especially the Force of Gravity. An analytical scale in which the suspended system is supported by the attraction and repulsion of permanent magnets and the force of a measured current in a coil, a light beam falling on differentially-connected photocells being used as indicator.

U. S. No. 2,560,326. A Barry. Iss. 7/10/51. App. 3/7/47. Assign. Standard Oil Development Co.

Clamping Device for Gravity Meters. A clamping system for an underwater gravimeter which is suspended as a pendulum from gimbals having a spring-actuated arm which engages a protrusion on the bottom of the instrument and is released by a solenoid whose current is controlled at the surface.

U. S. No. 2,560,366. H. E. Owen. Iss. 7/10/51. App. 12/30/47. Assign. Standard Oil Development Co.

Clamping Device for Force Responsive Elements. A remotely-controlled clamping device for an underwater gravimeter in which the clamping screw is motor driven through a friction clutch, the clamping arm striking stops at the clamped and the free positions to cause the clutch to slip which is indicated on an ammeter in the motor circuit.

U. S. No. 2,568,680. E. W. Frowe. Iss. 9/18/51. App. 11/28/49. Assign. Robert H. Ray Co.

Underwater Prospecting Device. A support for an underwater gravimeter having an external case carried on a bail and with an annular base plate having large holes and a vertical flange to eliminate zig-zagging of the instrument when it is raised and lowered in water.

MAGNETIC PROSPECTING

U. S. Re. 23,397 (Original No. 2,468,968). E. P. Felch, Jr. and T. Slonczewski. Iss. 8/7/51. App. 4/20/43 and 2/18/50. Assign. Bell Telephone Laboratories, Inc.

Magnetic Field Strength Indicator. A total-field magnetometer having three mutually-perpendicular flux-valves mounted on gimbals with two of the flux-valves controlling the orientation of the system through servomotors and with the outputs of the orienting flux-valves squared and combined with the output of the indicating flux-valve.

U. S. No. 2,559,586. B. S. Bjarnason. Iss. 7/10/51. App. 12/5/46. Assign. Hans T. F. Lundberg.

Instrument for and Method of Geophysical Exploration. An airborne magnetic variometer having a stabilized rectangular loop connected to a high-gain low-frequency amplifier and recorder.

U. S. No. 2,560,132. O. H. Schmitt. Iss. 7/10/51. App. 1/1/44. Assign. U.S.A.

Unbalanced Magnetometer. A two-element flux-valve type of magnetometer which is operated in an unbalanced condition by shunting one of the elements with an extraneous impedance.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,562,120. G. L. Pearson. Iss. 7/24/51. App. 8/26/48. Assign. Bell Telephone Laboratories, Inc.

Magnetic Field Strength Meter. A magnetometer having a thin strip of crystalline germanium with a current passed between two opposite edges and terminals on the other two opposite edges between which the Hall effect voltage is measured.

U. S. No. 2,564,854. G. Muffly. Iss. 8/21/51. App. 6/23/47. Assign. Gulf Research & Development Co.

Apparatus for Measuring Intensity of Magnetic Field. A magnetometer having a flux-valve with an asymmetric vane of magnetic material rotated about one end of the flux-valve, quadrature components of modulation of the flux-valve output being used to control orienting servomotors.

U. S. No. 2,565,799. W. H. Brattain. Iss. 8/28/51. App. 7/7/44. Assign. U.S.A.

Wave-Train Magnetometer. A flux-valve magnetometer whose output winding is part of a resonant circuit tuned to multi-frequency of the exciting frequency, and in which the envelope of the maximum amplitude of the resonant circuit is measured.

RADIOACTIVITY PROSPECTING

U. S. No. 2,562,914. G. Herzog. Iss. 8/7/51. App. 3/9/48. Assign. The Texas Co.

Prospecting. An airborne radioactivity-prospecting system in which the gamma-ray intensity is observed at an elevation which gives maximum contrast against background radiations.

U. S. No. 2,562,929. A. H. Lord, Jr. and E. Pancake. Iss. 8/7/51. App. 3/9/48. Assign. The Texas Co.

Prospecting. A radioactivity-prospecting method in which a directive detector mounted on a transit head is oriented in different directions and the response measured.

U. S. No. 2,562,961. W. M. Stratford and C. F. Teichmann and G. Herzog. Iss. 8/7/51. App. 3/9/48. Assign. The Texas Co.

Prospecting. A radioactivity-prospecting method in which samples are taken from locations having a minimum of background radiation and measuring the radioactivity of the samples and subtracting the background intensity at the location from which it is taken.

U. S. No. 2,562,962. W. M. Stratford. Iss. 8/7/51. App. 3/9/48 and 2/7/51. Assign. The Texas Co.

Prospecting. A radioactivity-prospecting method in which a sample of earth detritus is taken from a stream and its radioactivity compared with that of an equal mass of local rock, the survey progressing up the stream drainage system along the fork whose detritus sample has a higher ratio of activity.

U. S. No. 2,562,968. C. F. Teichmann, B. D. Lee and A. H. Lord, Jr. Iss. 8/7/51. App. 3/9/48. Assign. The Texas Co.

Prospecting. A radioactivity-prospecting system using two detectors one of which is shielded against cosmic rays and one shielded against gamma radiation from the earth, and the difference in response measured.

U. S. No. 2,562,969. C. F. Teichmann. Iss. 8/7/51. App. 6/2/49. Assign. Texaco Development Corp.

Radiation Detection. A gamma-ray detector having a fluorescent screen whose light is focussed by a lens or concave mirror onto a photosensitive film.

U. S. No. 2,563,333. G. Herzog. Iss. 8/7/51. App. 3/9/48. Assign. The Texas Co.

Geophysical Prospecting Using Gamma-Ray Detectors. A radioactivity-logging or prospecting system using two gamma-ray detectors having different detection efficiencies for different energies and comparing their responses.

SEISMIC PROSPECTING

U. S. No. 2,558,868. M. D. McCarty. Iss. 7/3/51. App. 7/1/46. Assign. Socony-Vacuum Oil Co., Inc.

Seismic Recording System. A seismograph recording system having three parallel filter channels each of which has a different time-gain control and with their outputs combined so as to give an optimum recording of direct, refracted, and reflected waves.

U. S. No. 2,558,924. N. B. Blake. Iss. 7/3/51. App. 11/20/45. Assign. Sun Oil Co.

Seismographic Prospecting Apparatus for Directing Explosive Energy. A seismograph shooting device having thick-walled shot-hole casing at the explosive and with a closure at its lower end, the casing carrying liquid above the bottom closure so that the closure is disrupted by the explosion.

U. S. No. 2,558,954. R. L. Hensen, Jr. Iss. 7/3/51. App. 9/12/46. Assign. Sun Oil Co.

Seismographic Prospecting Apparatus. A seismograph amplifier having a shot-released expander which also cuts off the avc until the later part of the record.

U. S. No. 2,562,983. D. H. Clewell. Iss. 8/7/51. App. 5/27/47. Assign. Socony-Vacuum Oil Co., Inc.

Frequency-Adjustable Seismic Wave Detector. A geophone having an armature adjustably attached to the moving system and attracted upward by a magnet attached to the case so as to introduce negative compliance and also support the weight of the moving mass.

U. S. No. 2,568,851. J. W. Flude. Iss. 9/25/51. App. 9/16/39, 3/7/42 and 5/14/47.

Detector Carrier for Seismic Exploration. A capsule-shaped seismometer case for use under water made from two cups, the lower one being heavier and supporting the detector unit.

U. S. No. 2,569,411. L. G. Ellis. Iss. 9/25/51. App. 3/25/49. Assign. Sun Oil Co.

Seismographic Prospecting. A method of reflection shooting in a well with an array of detectors on the surface near the well and recording a succession of shots of progressively-decreasing depth so that a record is obtained from shots below and above the reflecting horizons.

WELL LOGGING

U. S. No. 2,562,992. M. Schlumberger. Iss. 8/7/51. App. 10/29/46. Assign. Schlumberger Well Surveying Corp.

Well Logging System. An electric logging system in which the potential electrodes are in pairs with one of each pair being the same distance above the current electrode as its corresponding electrode below the current electrode.

U. S. No. 2,564,861. J. E. Sherborne. Iss. 8/21/51. App. 10/13/49. Assign. Union Oil Co. of Calif.

Method and Apparatus for Borehole Logging. A self-potential logging apparatus having a disc-type flexible electrode which contacts the formation with flexible insulating diaphragms above and below the electrode so as to isolate the formation from the main body of mud in the hole.

U. S. No. 2,568,241. P. W. Martin. Iss. 9/18/51. App. 11/8/44.

Apparatus for Logging. A system for logging-while-drilling in which the well apparatus produces an electrical impulse of fixed duration in the earth and the impulse is received at the surface and recorded.

U. S. No. 2,569,390. B. W. Sewell. Iss. 9/25/51. App. 8/20/46. Assign. Standard Oil Development Co.

Well Logging. A head for the kelly which permits running an electric cable down the drill stem while drilling and having two hollow arms between which the cable reel is journaled on a horizontal

axis and through which the mud may be circulated, electrical connections being made through slip rings concentric with the drill stem.

MISCELLANEOUS

U. S. No. 2,560,384. J. P. Crain. Iss. 7/10/51. App. 6/11/47. Assign. one-half to Albert H. Crain.

Marsh Buggy. A four-wheel-drive vehicle with large buoyant wheels which are independently driven by short chains to drive shafts.

U. S. No. 2,560,911. A. Wolf. Iss. 7/17/51. App. 7/24/47. Assign. Keystone Development Corp.

Acoustical Well Sounder. A sound generator and receiver assembly for a sonic fluid-level meter having a short barrel for firing a blank cartridge with a constricted annular passage around the barrel leading to a side chamber which contains an electromagnetic microphone protected by a baffle with a small orifice.

U. S. No. 2,565,951. R. R. Crookston and J. S. Waters. Iss. 8/28/51. App. 2/25/48. Assign. Standard Oil Development Co.

Drilling Rate Recorder. A drilling-rate recorder having a roller which is pressed against the live drilling line by air pressure from the drilling control and which mechanically integrates motion of the roller over 15 second intervals.

U. S. No. 2,569,328. A. C. Omberg. Iss. 9/25/51. App. 1/23/46. Assign. Bendix Aviation Corp.

Automatic Position Plotter. A device for plotting the position of an airplane on a map from the direction angles to two known radio stations compared with the compass bearing and using a computer to obtain the rectangular coordinates and drive a stylus across the map, the coordinates being reproduced on potentiometers whose signal is returned to the computer.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE THIRD QUARTER OF 1951

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2,558,743	460	2,559,687	48	2,560,818	316
2,558,758	316	2,559,688	416	2,560,834[a]	132
2,558,850	16	2,559,718	68, 16	2,560,852	288
2,558,868[a]	360, 372	2,559,800	428	2,560,911[a]	408
2,558,919	308	2,559,919[a]	180	2,561,077	460
2,558,924[a]	360, 136	2,559,972	308	2,561,084	484
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2,559,511	316	2,560,452	136	2,561,365	224
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2,559,586[a]	232	2,560,483	224	2,561,368	484, 436
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[a] Abstracted on preceding pages of this issue.

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2,561,490	416
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2,561,747	372
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2,561,869	324
2,562,109	12
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2,562,449	140
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2,562,975	492
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2,562,983[a]	376
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2,566,570	200
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2,567,682	16	2,568,441	316	2,568,932	68
2,567,755	460	2,568,538	316	2,568,940	428
2,567,756	460	2,568,568	312	2,569,032	236
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REVIEWS

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The Earth's Magnetism, by Sydney Chapman, Methuen & Co., Ltd., London, John Wiley and Sons, Inc., New York, second edition, 1951, xi+127 pp., $1.50.

This member of the series, "Methuen's Monographs on Physical Subjects," might be roughly described as a vest pocket edition of the nearly 1,100 page unabridged treatise, *Geomagnetism*, by Chapman and Bartels. Actually, since the latter was published in 1940, the monograph being reviewed is more up-to-date and, since its first edition was published in 1936, the "abridgment" was historically in reverse.

Only a few paragraphs are devoted to the prospecting uses of terrestrial magnetism. The object of the book is the description and explanation of the earth's main magnetic field and its complicated variations, a subject in which the author is an acknowledged authority. The six chapters have the following titles: The main field and the secular variation, The transient magnetic variations, The quiet-day solar daily magnetic variation S_q, The lunar daily magnetic variation L, The morphology

of the magnetic disturbance field D, Solar relations with magnetic disturbance. Mathematical details are omitted but can be filled in by those interested who have a background of potential theory and harmonic analysis. The book is definitely not written down to a layman's level; however, geophysicists and others with good training in physical science should have no difficulty in following the text.

The mechanical details have been well cared for. The only errors noticed were the following: page 45, in two places on the time scales of Figure 12, "18" and "20" should be "20" and "24" respectively; page 84, "S_q" in the last line should be "S_D"; page 88, last line, and page 89, first line, "(a)" and "(b) and (c)" should be interchanged. It also would have been well to mention in connection with Figure 14 on page 47 that declination is sometimes measured in gamma as west force, as well as in angular measure.

A surprising amount of factual information is included. When it is noted that the actual text runs to only 116 pages and includes 39 figures, it is evident that the book is a marvel of condensation. The later pages are used for a list of suggestions for further reading and three indexes. The book should be very useful as an introduction to and an orientation in the study of the earth's magnetism.

THOMAS A. ELKINS

Climate in Everyday Life, by C. E. P. Brooks, The Philosophical Library, Inc., New York, 1951, 314 pp., $4.50.

It is seldom that the reviewer sees a book which can serve so successfully as an authoritative reference work but is also written in an interesting and provocative manner. It is a compendium of climatological facts presented on a world-wide scale and can be used to good advantage by those responsible for initiating exploration programs in any part of the world. The book contains many full-page global maps on which such information is presented as the maximum rainfall in one hour to be expected once every two years, the number of lightning flashes to ground per square mile per year, the distribution of tornadoes, hurricanes, or typhoons, and tropical cyclones, the probable maximum temperature of a surface exposed to the sun (which can be more than 180°F. and in extreme cases 200°F.), and an index of deterioration, in which the effects of temperature, humidity, and wind velocity have been combined in one equation, and the results plotted on a map. In addition to these charts, there are a number of tables for the major cities of the world giving the average duration of bright sunshine in hours per day for each month, the dates of closing and opening of ports; a thirteen-page table in the appendix summarizes the climates of more than 300 cities including such facts as latitude, longitude, elevation above sea level, the mean annual temperature, as well as that for January and July, the mean annual maximum and minimum temperatures, the relative humidity for January and July, the annual rainfall, the wettest and dryest months, the number of days of rain per year, and the average number of hours between sunrise and sunset for each two degrees of latitude for the twelve months of the year. These tables and global charts are in addition to the ones which would be expected in a book on climatology, such as those dealing with seasonal temperature and humidity variations, and types of climate.

The book is divided into three main parts entitled Living with the Climate, Climate as an Enemy, and the Control of Climate. Each section consists of an integrated, self-sufficient discussion of the major topics on each of these subjects, with particular reference to economic aspects. In the section on Climate as an Enemy, emphasis is given to a discussion of the deterioration of materials in various climates, and on atmospheric pollution, with particular reference to examples in England. For those interested in the optimum type of construction and design of houses and factories as well as their location with respect to the sun, the chapter in which these factors are discussed in detail, including quantitative approaches, should prove valuable. The section on the Control of Climate includes chapters on heating, air conditioning, lighting, and clothing, as well as a series of brief discussions summarizing attempts by man to make rain, disperse fog, prevent hail and frost, and protect himself from lightning. A comprehensive list of references is also included, so that those wishing to obtain additional information on many of the varied subjects presented in this book can use the current literature efficiently.

As one might expect in a book of this type, the author cannot refrain from speculating on the correlation between climates and civilizations, although many of his remarks are taken from a book by S. F. Markham, *Climate and the Energy of Nations*, London (Milford, Oxford University Press). He states, "S. F. Markham in a fascinating book points out that civilisation developed first in those parts of the world which enjoyed an average climate nearest to the ideal, i.e., the subtropics, but in those regions there are many hours of day and even whole seasons when the weather is too hot or too humid for full efficiency. Consequently, as methods of heating improved and the winter temperature became less important the centres of civilisation moved to higher latitudes where the summers are less enervating." The thoughts expressed in this quotation differ to some degree from Brooks's opinion of the climate in the Gulf Coast, which afforded the reviewer some slight amusement upon reading it, having lived there for a number of years. He states, "The northernmost parts of India, especially the high level valleys such as Kashmir, are almost temperate, and are probably no less suitable for Europeans than are the Gulf states of the U.S.A., provided that reasonable sanitary precautions are taken and the head is kept covered against the sun in the hottest parts of the day." In spite of these naive remarks regarding the climate of the Gulf States, this book is recommended highly to those geophysicists and geologists who are responsible for the planning and conduct of exploration programs outside the United States as an authoritative and detailed source of information, presented in a very readable and interesting form.

RICHARD A. GEYER

The Formation of Mineral Deposits, by Alan M. Bateman, John Wiley and Sons, Inc., New York, 1951, 371 pp.

Having observed a widespread interest on the part of the general public as to the source of useful minerals, Professor Bateman has endeavored in this book to describe the origin and occurrence of various mineral deposits in language that can be understood by those without geological training. The book is essentially a condensation and simplification of his recent *Economic Mineral Deposits*, reviewed in the October, 1950 issue of *Geophysics*.

The major part of the book is devoted to the processes by which mineral deposits form. Magmatic, metasomatic, hydrothermal, sedimentary, weathering, and metamorphic processes are each given a separate chapter, that on sedimentary mechanisms being the longest. Some questions of definition may be raised by the author's discussion of petroleum and natural gas, as well as of ground water, as mineral deposits.

A 34-page chapter on Exploration and Exploitation hastily discusses all geophysical methods in 13 pages. Mining methods, ore dressing, and refining are also covered here. The final chapter summarizes the distribution of mineral resources among the nations of the world.

This book should be especially useful for those engaged in geophysical work who have not had the opportunity to study economic geology and who wish to broaden their background in other branches of exploration. If the volume of geophysical activity in the mining field should increase substantially in the future, many now working in petroleum geophysics may find it to their advantage to have some familiarity with the principles of mineral accumulation. This book is recommended as a primer for any who may wish to prepare themselves for this possibility.

MILTON B. DOBRIN
Magnolia Petroleum Company

Erdoel in der Sowjetunion, by Heinrich Hassmann, von Hernhaussen K.G., Hamburg, 1951, 176 pp.

Much of the statistical information presented in this book is based on the latest data available in the trade journals, as well as from several books published within the last decade. However, the author warns in his preface of the reliability of the statistics presented subsequent to 1938. Trade journals, particularly those published in Europe, such as *Erdoel und Kohle*, as well as *World Oil* and the *Oil and*

Gas Journal, comprise the major sources of information. Emphasis in this book is placed on production statistics, geographical location of oil fields, historical aspects, and geopolitics. Reference to technical subjects involved in the exploration and production of oil is limited to several brief chapters in one section. A discussion of petroleum geology and geophysics is confined primarily to six pages, and five pages are allotted to production techniques. The main section headings include: Fundamentals, The Development, A Geographic Discussion, and Problems of the Russian Oil Industry.

This book is recommended to anyone interested in the history, economics, geography, and geopolitical aspects of the Russian oil industry. For those interested in the status of their industry during the Czarist regime, it is also an important source of information, because this phase of the historical discussion begins with the year 1821. Some interesting information is also presented in the appendix in terms of a summary of Russian oil production from 1861 to 1950 compared with world-wide production figures, and with United States production. The source of the data through 1946 is from the American publication *World Oil* and from 1947 through 1950 from other sources. A useful comparative glossary of terms frequently found in oil industry literature for England, Germany, United States, and Russia is also presented in the appendix.

RICHARD A. GEYER

Gravity Effect of Earth Tides, by B. Baars, Private Publication of N. V. DeBataafsche Petroleum Maatschappij, Geological Department, The Hague.

Tidal Variations of Gravity, by M. S. Redford, *Trans. Am. Geophys. Union*, Vol. 32, No. 2, April 1951, pp. 151–156.

Harmonic Analysis of Gravity Observations, by Albert J. Hoskinson, *Trans. Am. Geophys. Union*, Vol. 32, No. 2, April 1951, pp. 163–165.

These three publications are all concerned with the simultaneous, world-wide series of tidal gravity observations initiated by Dr. A. Van Weelden and carried out by the Shell organization and other co-operating companies and institutions. The primary data were obtained at 26 stations, three with two gravimeters each, with readings at 15 minute intervals over the period from May 9 to May 23, 1949.

Baars' paper is a general report on all the results. Redford's paper analyzes the Toronto data only, where the observations were extended to June 9, Hoskinson's paper gives the results of a harmonic analysis for the magnitudes of five of the tide-producing components in 17 sets of readings in the United States, Mexico, and Canada.

This program was by far the most widespread and longest group series of observations of tidal gravity observations which has yet been carried out. Stations were in Holland at The Hague, in Nigeria at Owerri, in Egypt at Helwan, in Indonesia at Pladju and Balikpapan, in Dutch Guinea at Sarong, in Canada at Toronto, Ottawa and Edmonton, in Hawaii at Honolulu, in Mexico at Panuco, Cosoleacaque and Muna, in Trinidad at Point Fortin, in Venezuela at Maracaibo, in Colombia at Puerto Colombia and Bogota, and in the United States at Salt Lake, Ft. Morgan, Tulsa, Washington, Albuquerque, Austin, Beaumont, Houston and Pasadena. Observations were made with North American, LaCoste-Romberg, Worden, Western, Humble, Mott-Smith, and Carter gravimeters.

The results were all analyzed in the same manner by the Shell staff at The Hague. Instrument drift was removed as a 24 hour running average. Baars' paper gives two diagrams for each series of observations; the first is a plot of observed vs. calculated amplitudes, while the second is the ratios of observed to calculated amplitudes vs. calculated amplitudes. ("Calculated" values are the gravitational forces of the sun and moon, assuming a rigid earth.) No systematic or conclusive phase differences were found between calculated and observed effects.

The most probable value of the ratio of observed to calculated amplitudes, from all the observations, is $d = 1.22$. The difference from unity is a measure of the yielding of the earth to the tidal forces. The above value is consistent with the magnitudes of earth constants derived from other considerations. The absence of any phase shift also is in agreement with theory.

The values of d from the different stations (omitting three unsatisfactory ones) range from 1.06 to 1.33 and the standard deviation is 0.18 when the determinations of the ratios exclude amplitudes less than 0.1 mg. There is no systematic relation between the values of d and the geology or geography of the stations; shield and basin, island, coastal and mountain locations are included. Apparently, the water tides of the ocean do not affect the gravity appreciably either by direct mass effects or by loading. For example, stations in very different situations, such as Ottawa, Beaumont, and Honolulu, gave ratios of 1.21, 1.22 and 1.29. These differences are about the same as the differences between the pairs of values for the ratios at the three stations (Houston, Edmonton, and Sarong) where two instruments were set up side by side.

The papers of Redford and Hoskinson give the results of determinations of the amplitudes of several of the components of the tidal gravity by harmonic analysis. Redford uses a more elaborate method for calculating drift than the 24 hour running average. The results are not very different, however, as is shown by the following table for the analysis of the Toronto data which are common to the three papers.

Ratios of Harmonic Components to Theoretical for Rigid Earth

	M_2	S_2	N_2	K_1	O_1	*Average*
Baars	—	—	—	—	—	1.06
Redford	1.08	1.11	1.13	0.92	1.04	1.06
Hoskinson	1.19	1.18	0.96	0.94	—	1.05

From the practical standpoint of the field operation of gravimeters the most important result is the indication that there is no definite basis for local variation of the ratio of the observed amplitudes to those calculated for a rigid earth. This means that if tidal corrections to gravimeter drift curves are applied, which may be justified for long intervals between base readings with very stable instruments, such corrections may be calculated as those for a rigid earth multiplied by a factor of about 1.22. This is in accordance with Adler's[1] suggestion made some 10 years ago on the basis of observations by Wolf[2] at Tulsa.

[1] Joseph L. Adler, *Geophysics, VII*, No. 1 (1942), 36.

[2] Alfred Wolf, *Geophysics, V*, No. 4 (1940), 317–320. *Geophysics, VI*, No. 1 (1941), 81–83.

L. L. NETTLETON

"Colloquium on Plastic Flow and Deformation Within the Earth," Hershey, Pennsylvania, September 12–14, 1950.

Transactions American Geophysical Union, Vol. 32, No. 4, Aug. 1951, pp. 499–543.

This colloquium presents a discussion of facts and theories concerning movements of the earth's crust and interior.

The first few articles (J. M. Burgers, A. Nadai, D. Griggs) outline the basic tenets of theoretical and experimental rheology. Burgers shows the distinction between permanent and recoverable deformation γ_p and γ_e and emphasizes the fact that both are functions of time. The yield stress is defined as the value of stress above which permanent deformation large in comparison with the recoverable strain is obtained. Curves of γ_p plotted as functions of time with stress τ as a parameter are the flow lines characteristic of a given material for given temperature and pressures. $d\gamma_p/d\tau=\dot{\gamma}_p$ is the rate of strain and $d\tau/d\dot{\gamma}_p=\phi$ is the viscosity. In a solid the viscosity will in general be non-Newtonian, i.e. ϕ will be a function of stress. Before any truly quantitative theories concerning plastic deformation of the earth can be formulated, determinations of ϕ as a function of pressure, time and stress must be made for the actual materials and conditions pertaining at various depths in the earth (Nadai). So far conditions of pressure and temperature approximating those at depths of 0 to 10 km have been reproducible in laboratory experiments (Griggs). The work of Griggs in this field has shown the great importance of temperature, confining pressure, and the presence of solvents. Thus at 1,000 bars and 400°C. in water vapor, quartz aggregates will flow under shear though single dry quartz crystals will only fracture (even under small stresses, if these be maintained long enough). Such effects are as yet

outside of the realm of theoretical rheology and may lower yield points by one or several orders of magnitude. This is in accord with Gutenberg's and Richter's results showing that the maximum energy release in deep focus earthquakes is an order of magnitude less than for shallow shocks.

Benioff shows that if J be the total energy released by an earthquake and ϵ the average elastic strain preceding an earthquake, one must have the relation $J^{1/2}=\epsilon C$, C being a constant. Since J can be obtained from Gutenberg-Richter magnitudes, he has plotted the accumulated sum of the $J^{1/2}$ increments beginning with the year 1904. He thus obtains a series of elastic strain rebound characteristics for all major shallow, intermediate, and deep earthquakes. From these characteristics he was able to discover several significant features: The great shallow earthquakes are not independent but are probably related to a single world wide stress system. The rate of total secular strain generation has been very constant since 1908. The strain was released during active periods of decreasing duration separated by quiescent periods. The duration of these periods has been decreasing as $1/t$ since 1904, so that today strain is being released almost as fast as it is being generated. Intermediate foci (70 to 300 km depth) seem to exhibit longer periods. Deep foci (300 to 700 km) do not show periodicities but plot on a straight line. The activity at these depths has been decreasing since 1904. Considerable plastic flow must be occurring. Thus, starting with a few very simple physical considerations Benioff has produced a powerful new tool for studying the tectonic properties of the Earth's interior.

The papers enumerated so far summarize some theoretical considerations, laboratory experiments and seismological observations pertaining to plasticity and elasticity within the Earth. However an important part of today's knowledge concerning the plastic and tectonic properties of the Earth's interior is due to geological studies of areas of past and present tectonic activity. Several geological papers form part of this colloquium (Bucher, Hess). Bucher describes some of the basic characteristics of orogenic belts. He points out that a thorough knowledge of their properties is essential before any physical theory of the Earth can be formulated. He pictures all major orogenic belts as being formed of vast amounts of sediment deposited in geosynclines which were subsequently folded. Though the curvature of some mountain arcs may be extreme, the folding remains parallel to the trend of the arc. The major orogenic belts are aligned along several well defined zones. During the period to which geological observation can be applied ($3 \cdot 10^8$ years), the evolution of many such belts can be followed from the birth of a geosyncline through the active period to the time when the stresses are finally relieved and all tectonic activity has ceased. The great elevation of young orogenic belts is due to isostatic adjustment. Their history is intimately related to the origin of granites which would be a product of orogeny and metamorphism.

According to Bijlaard, downbuckling of the earth's crust cannot occur without plastic flow. Plastic deformation strips must form at points where the global stress patterns reach their maxima. The crust would thicken at these points and isostatic readjustment would tend to produce downbuckling which would be further enhanced by still active compressional forces and increased sedimentation in the depression. Vening-Meinesz agrees with this suggestion. He thinks that the geometry of the two tectonic arcs in Indonesia would obey a formula given by Bijlaard for the formation of lines of plastic flow in an elastic plate under compression.

Bullard remarks that there are two theories as to the causes of deformation in the earth's crust. The first is the Jeffries contraction theory which might not be as contrary to geological evidence as sometimes claimed. However it appears to contradict a new trend in cosmological thinking according to which the earth began its history as a cool body. The second is the Hess-Griggs-Vening-Meinesz convection current hypothesis which does not run into this difficulty but still needs experimental substantiation. This might be provided by heat flow measurements.

Glangeaud's theory of thermodynamic gradients postulates the existence of horizontal variations of thermodynamic variables resulting in the formation of potential orogenic zones. Though their existence alone would not result in orogenic phenomena, their presence might explain the localization of orogenic zones, independently of their cause.

Hess points out that the persistence of mountain roots without compensating surface elevations is a strong argument in favor of the convection theory, since this can only be explained by viscous drag, whether the downbuckling be elastic or plastic.

Some of the geodetic evidence concerning the plasticity of the earth's interior is summarized by Heiskanen who justly states that the only quantitative information about the viscosity of the subcrustal layers is provided by the detailed gravity and elevation surveys in Fennoscandia. The rate of uplift due to release of the ice load gives a viscosity of 10^{22} poises, providing that this viscosity is assumed to be Newtonian. The case of time dependent viscosity has not yet been amenable to calculation. Another highly significant contribution of geodesy was the discovery of large regional anomalies in tectonically quiet areas. If the anti-root hypothesis be accepted, the dimensions of these areas indicate that the depth at which the upper layers of the earth are first compensated would be near the lower limit of the deep focus earthquake zone.

An article by Birch suggests that the variations of elastic properties with depth as determined by seismologists cannot be explained on the basis of pressure alone, but that a change of state between 200 and 1,000 km depth must occur. The effect of such a discontinuity upon convection currents is uncertain.

Cox and Vening-Meinesz discuss possible relative motions of the Earth's crust over its interior. There are no conclusive observational data on this subject.

Finally, a paper by Vestine mentions that, according to recent theories by Lamar, Elsasser, and Bullard, there might be a very intimate connection between deep seated plastic flow and the secular variations of the Earth's magnetic field. It may even be that these currents are the cause of geomagnetism.

These authoritative articles should be of great value to anyone interested in the broader aspects of geophysics and geology. They show how essential it is to unify the knowledge available to us from different fields if we are ever to bridge the gap between speculation and fact. Though no unified theory of terrestrial phenomena can be expected for many years to come, hitherto unrelated facts are beginning to fit into an over-all pattern. Laboratory experiments, the study of earthquakes, mountain ranges, gravity anomalies, geomagnetism, etc., all confirm the fundamental role of plastic phenomena within the Earth. Today, when each branch of science has been subdivided into innumerable highly specialized fields, colloquia such as this are a *sine qua non* for the progress of knowledge.

IVAN TOLSTOY

Misure Gravimetriche nelle Grotte di Castellana (Gravimetric Measurements in the Caves of Castellana), by G. Boaga, G. Tribalto and G. Zaccara, *Annali di Geofisica*, Vol. III, No. 4, Oct. 1950, pp. 439–449.

The grotto of Castellana, in Italy, discovered in 1938, is about a thousand meters long underground and practically level, as is the surface of the ground above it. It thus affords a perfect opportunity to measure gravity values both on the surface and some sixty meters below on the same vertical line. The authors of this paper made twenty-two such sets of measurements, using a Western gravimeter. In six cases the surface measurement was not made but was replaced by a value found from interpolation of values at nearby stations.

Most of the calculations are based on the formula

$$dg = 4\pi\epsilon(\tfrac{2}{3}\Delta - \rho)\cdot\Delta Q, \qquad (1)$$

where dg is the difference between the underground and the surface gravity,

ϵ is the gravitational constant,

Δ the mean density of the earth,

ρ the surface density, and

ΔQ the difference between the surface and the underground elevations.

If Δ is taken as 5.52 g/cm³, values of ρ can be computed by (1) from the dg values. A mean value of 2.23 gm/cm³ for the surface density is given on page 444 but this must be a misprint since calculation from the data of Table III yields the value 2.27 gm/cm³. Conversely, assuming ρ known, values of

Δ can be computed from (1). The mean values thus found, omitting three stations which seem to be anomalous, are:

for $\rho = 2.20$, $\Delta = 5.38$,
$\rho = 2.25$, $\Delta = 5.46$,
$\rho = 2.30$, $\Delta = 5.64$.

Finally, the surface stations were reduced to the positions of the underground stations, using the ordinary free air and Bouguer corrections for the surface stations and the Bouguer correction with reversed sign for the underground stations. The results, which exhibit a mean error (without regard to sign) ranging from 0.62 to 0.75 mgal for the three densities listed above, are regarded as justifying the use of these corrections for gravimetric reductions to the geoid. This last conclusion is the same as that reached by E. Soler on the basis of similar pendulum measurements made in 1923 in and above grottos near Trieste. Soler's work, listed in the bibliography on page 449, inspired the present article.

The mean square error given for the mean surface density value of 2.27 gm/cm³ is 0.04 gm/cm³. However, the values averaged vary from 1.68 to 2.49 gm/cm³, and the frequency distribution is so erratic that the mean square error does not have much meaning here as an indication of the accuracy of the mean surface density value. Comments on the causes of the variations in the density values found at the separate stations would have been helpful since such variations appear to be the limiting factor on the accuracy of this method of computing surface density and the mean density of the earth.

Comprehensive tables of data and excellent maps complete this interesting article.

THOMAS A. ELKINS

Zur refraktionsseismischen Bestimmung des Randes und der Flanke von Salzstocken. (On the determination by seismic refraction of the borders and flanks of salt stocks), by G. Brinckmeier and H. von Helms, *Erdöl und Kohle*, Heft 5, 1951, pp. 321–326.

From the title of this article, one might expect it to deal with the detailed mapping of salt-dome boundaries by use of seismic detectors deep in wells that flank or penetrate the domes themselves. This technique, which has been described by Gardner,[1] has been quite successful as a means of detailing known domes. Brinckmeier and von Helms propose a method for obtaining the same type of information by standard profile shooting across the top of the dome. Their system appears so unworkable that it would scarcely merit any space for review except as a glaring example of how seismic data should *not* be interpreted.

Imitating the well-known procedures of gravity and magnetic analysis, in which the effects of various simple models are calculated for comparison with observed data, the authors set up eleven type configurations of salt domes and adjacent formations and compute the time-distance curves that would be expected with each model. Some examples of their models: dome with flat top and vertical sides surrounded by sediments of uniform and much lower speed, dome with sloping sides similarly surrounded; dome with vertical flanks and one high-speed horizontal high-velocity marker bed in contact with sides; same dome with sloping marker bed; dome with overhang and sloping marker, etc. Time-distance curves are systematically computed for shots in reverse directions across the top of each dome; one can presumably determine what kind of dome he has encountered by comparing his observed time-distance curves with the various computed curves.

The authors themselves acknowledge that it is more difficult to deduce unknown salt domes by this means than to compute their model curves. Their admission, however, stops far short of the mark. The ambiguity of this method is so great that it would be worthless in detailing any real dome. It has long been realized that computed fields from assumed models can only be used in gravity or magnetic interpretation when there is a great deal of independent geologic control, and even then only with the utmost caution. It is regretted that the authors do not apply the same conservatism to the interpretation of seismic time-distance curves.

MILTON B. DOBRIN

[1] L. W. Gardner, Seismograph Determination of Salt-Dome Boundary Using Well Detector *Geophysics*, XIV, pp. 29–38, 1949.

The Gravitational and Magnetic Exploration of Parts of the Mesozoic-Covered Areas of South-Central England, by Norman L. Falcon and Leslie H. Tarrant, *Quart. Journal Geol. Soc.*, Vol. CVI, Pt. 2, 1951, pp. 141–170, 7 maps, 8 figures.

This informative and well prepared paper concerns the search by the D'Arcy Exploration Co., Ltd. (exploration subsidiary of the Anglo-Iranian Oil Co.) for additional areas and structures favoring the occurrence of oil following their discovery of a small group of commercially profitable oil fields in concealed Upper Carboniferous rocks in the Eakring area of Nottinghamshire.

Studies by Anglo-Iranian and others, based on a limited number of bore holes and coal mine workings, had pointed to an extensive region in the foreland and foredeep of the Variscan (Late Paleozoic) mountain system whose basement core is now exposed in Cornwall and Devon. While it is suspected that structures in the more southerly part of this region may be too close to the Varissan axis and thus have lost any oil accumulations, it is also believed that the more gentle folds to the north may well have retained them. The area selected for gravity and magnetic work is in the more favored northern part and amounts to some 6,000 square miles extending in an east-west strip from the mouth of the Thames westward about 140 miles to the mouth of the Severn River. The surveys were made during the years 1945–1949 using a Frost gravity meter and Watts vertical intensity magnetometers. The density of gravity stations is about two per square mile but that of the magnetic stations only one per two square miles. The accuracy of the gravity work is believed to be ± 0.1 milligal for the flat areas and ± 0.3 milligal for the most hilly areas. The accuracy of the magnetic work is about ± 5 gammas. The results are presented on maps with scale of ten miles to the inch; the gravity contour interval is one milligal and the magnetic 25 gammas.

The geophysical problem is twofold. From the regional variations of gravity and magnetic intensity there are sought indications of those areas believed most likely to have a considerable thickness of Upper Carboniferous rocks, and from the more local variations there are sought indications of anticlinal folding. The gravity and magnetic surveys are considered to be only preliminary work, but they have encouraged the company to expect an appreciable thickness of the desired Upper Carboniferous under the Mesozoic cover in several parts of the surveyed area. Preliminary seismic coverage by D'Arcy has already begun in the western and central parts of the area, and the results support the gravity interpretations given in the paper.

The preliminary gravity surveys made over certain parts of the area where the Paleozoic geology is known from borings and mine workings, as well as some gravity observations made at several levels in mine workings, indicated that the density contrast between the lighter Upper Carboniferous (Coal Measures) and other pre-Mesozoic rocks is large enough to allow substantial variations in the thickness of the former to cause measurable changes in gravity. They also showed that the density contrast between the overlying Mesozoic and the Upper Carboniferous or older Paleozoic rocks is of such magnitude that the effect of thickness variations of the Mesozoic must be removed before using the simplifying assumption that areas of lower gravity on the corrected Bouguer map are associated with larger Upper Carboniferous thicknesses. This assumption, the authors admit, is an optimistic one and may be considerably in error. The gravity variations may actually be due, in part at least to both deeper masses of density contrast such as intrabasement intrusions or shallower masses such as unexpected troughs of lighter Triassic sediments.

A map is presented which shows the positions and trends of the "boldest and most convincing local or residual gravity anomalies" and the positions and axes of structures deduced from surface geology. The authors claim to have been quite objective in their determinations of the residuals yet every one of the twelve structures mapped by surface work has a reflection in the gravity picture. The manner of disentangling regional and local effects is not described in detail. It is stated only that the residual gravity highs have been deduced by subtracting the estimated regional gravity gradient from the Bouguer anomaly.

Of particular interest are the statistical studies the authors present to determine likely density contrasts and the probabilities that the gravity variations, corrected for known or interpolated thickness variations of the Mesozoic cover, really give an indication of Upper Carboniferous thicknesses.

The magnetic data is used largely to estimate order of magnitude of basement depth. This taken together with Mesozoic thickness gives hints of pre-Mesozoic thickness. The inferences possible from the magnetic results give qualitative confirmation of the gravity interpretation in many places. It would seem to the reviewer that a higher density of magnetic stations equal to or even greater than that of the gravity would have added much to the results furnished by this method.

ROBERT J. WATSON

Dating Late-Pleistocene Events by Means of Radiocarbon, by Richard Foster Flint, *Nature*, Vol. 167, May 26, 1951.

This condensation of a lecture made at University College, London outlines the radiocarbon method of dating and also some of the results obtained. It should, therefore, be of interest to those who have not followed the work in detail. So far the method is only applicable to dating events within the last 20,000 years. However, quite an array of dates in this period have been obtained. For example, it has been estimated that Mt. Mazama, Oregon, blew its top $6{,}453 \pm 250$ years ago; the hole which resulted is now filled by Crater Lake. The Mankato glacial period is covered in somewhat more detail.

LYNN G. HOWELL

Studies on Tusnami on the Pacific Coasts of Northern Honshu, by Sekiji Ogiwara and Toshijichi Okita, The Science Reports of the Tohoku University, Fifth Series, *Geophysics*, II, No. 1, March 1950.

The authors present the results of a model study of Shizukawa Harbor for the conditions prior to and after the 1933 Tsunami. The over-all model was 120 cm by 240 cm. Froude scaling was used with a horizontal ratio of 1:1,500 and vertical ratio of 1:125. Some details as to model construction and instrumentation are given.

The results are thoroughly discussed and are grouped in five categories. 1) Maximum wave height observed at various stations. 2) Travel time of the first crest of the waves. 3) Wave form within the harbor. 4) Period of the secondary undulation, and 5) The effect of viscosity.

Concerning 5) authors were able to show that Froudian scaling was satisfied fairly well even when viscosity is taken into account.

In conclusion, the authors recommend certain breakwater improvements to lessen future damage.

HARLOW G. FARMER, JR.
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PUBLICATIONS RECEIVED

Listed below are all publications received at the business office of the society on subscription and through free exchange for *Geophysics* since publication of the last issue. Periodicals and separates indicated by the asterisk (*) have been forwarded to the Standing Committee on Reviews, and will be placed in the permanent depository of the society at the University of Tulsa Library. These publications are available for loan to members of the society on application to the business manager. Other publications will be held for a short time at the business office. Disposition of books listed is by direction of the Standing Committee on Reviews.

Periodicals

**American Journal of Science*, Vol. 249, Nos. 9, 10, 11 (Sept., Oct., Nov., 1951)
**Annales de Geophysique*, Vol. 7, Nos. 2 & 3 (Apr.–June & July–Sept., 1951).
**Annali di Geofisica*, Vol. 4, No. 3 (July, 1951)
**Boletin de la Associacion Mexicana de Geologos Petroleros*, Vol. 3, No. 1–2 (Jan.–Feb., 1951)
Bulletin of the AAPG, Vol. 35, Nos. 9, 10, 11 (Sept., Oct., Nov., 1951)
**Bulletin of the Earthquake Research Institute* (Tokyo University), Vol. 25, No. 3–4 (July–Dec., 1950)
**Bulletin of the Hungarian Geological Society*, Vol. 81, No. 4–6 (1951)
**Bulletin of the Seismological Society of America*, Vol. 41, No. 3 (July, 1951)
**Committee on Geophysics and Geography, RDB, Articals on Geophysics in Current Russian Periodicals*, List No. 33 (Aug. 28, 1951)
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DISCUSSIONS AND COMMUNICATIONS

THE RECENT PROGRESS OF THE GRAVITY PROGRAM OF THE COLUMBUS GROUP*

DR. R. A. HIRVONEN†

The world-wide gravity program of the Mapping and Charting Research Laboratory of Ohio State University has been described for this society at the last annual meeting by Dr. W. Heiskanan, who was invited by Prof. G. H. Harding, director of the laboratory, to plan this program and to function as the scientific leader for its realization.

To put it briefly: The aim of this project is to create an absolute world system of coordinates, to which system all existing and future triangulations can be converted. The fundamental work to be carried out in this program is the collection of all existing gravity observations in the world and the performance of the necexsary reductions. After this is achieved, the following problems can be dealt with:

1) Computing of the difference between the surfaces of the geoid and the international ellipsoid presently in use,
2) Computing of the deflections of the vertical, in the first place at the principal points of triangulations,
3) Control of small-scale maps up to 1:100,000 of isolated areas,
4) Computing of long geodetic distances, for example, over the oceans,
5) Improvement of the dimensions of the international ellipsoid.

This program has been explained in a more detailed way by Dr. Heiskanen in his paper "On the World Geodetic System," which was published by the Finnish Geodetic Institute last June. At this point I consider it appropriate to review the investigations that have been made on the same subject before in various countries in order to clarify where we stand right now.

As we know, the theoretical background was furnished by the famous Stokes' formula of 1849 which gives the difference between the geoid and the spheroid, provided the gravity anomlaies are known over the entire earth. The practical application of this was not possible until *Vening Meinesz* developed the relevant methoo of gravity measurements at sea. In 1930, so large a number of observations was available that the first attempts were ventured. An Austrian, Dr. *Ackerl*, inspired by the late Prof. Hopfner, carried out the first world-wide calculations. Due to several pecularities in Hopfner's version of the theory, the results were quite misleading. The deviations of the geoid amounted often to more than thousands of meters and systematically had a wrong sign. Prof. Heiskanen entrusted me in 1934 to make a new attempt, maintaining strictly the orthodox and currently accepted theoretical basis. The simple free air anomalies were used. Four thousand four hundred and ten gravity observations were available. For the unobserved parts of the earth it was assumed that the anomalies were equal and opposite to the isostatic reductions which were roughly estimated. The elevations were calculated only for points surrounded by reliable observations. The greatest deviation of the geoid was found near the Himalaya, -115 m. As an average the deviations amounted to ± 50 m, precisely as predicted by *Helmert* thirty years earlier. The accuracy of the results was estimated rather generously to be ± 50 m also, but nevertheless this does not make the results illusory because the errors are of the slowly undulating systematic kind.

As to the conclusion of the pendulum era of gravity observations, a new calculation was performed by the late Dr. Tanni in the Isostatic Institute, Helsinki, in 1948. The gravity observations had

* Presented at the Eastern Regional Meeting of the Society of Exploration Geophysicists, Pittsburgh, October 25, 1951.

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been increased threefold, containing about 13,000 pendulum observations and, due to the isostatic reductions, every observation was more representative of its surroundings than my free-air anomalies had been. The number of points where the elevation of the geoid could be calculated with some reliability was 218 instead of my 62. The greatest depression of the geoid was now in the South Cape of India, amounting to only −64 m. As an average, the undulations were ±26 m and their accuracy ±10 m, at least in the more densely observed regions.

In the year 1928 Vening Meinesz modified the Stokes' formula so as to give the components of the deflection of the vertical on the basis of gravity anomalies. In this case a dense local net of anomalies is necessary but the distant zones have much less significance than the elevations. Several practical applications have been carried out. I limit myself to giving the results in the form of a table:

Author	Year	Country	Points	Radius	Accuracy
Kasansky	1934	USSR	26	110 km	±0.8″
Steenwijk	1948	Indonesia	150	512 km	—
Cook	1950	England	4	550 km	—
Hopmann	1950	Germany	1	5500 km	—
Rice	1951	U.S.A.	16	300–600 km	±0.5″ for ξ ±0.7″ for η

The figures under "Radius" reveal the fact that the integration has not been extended over the whole earth. Accordingly the deflections are not absolute but relative within the area considered. The accuracy, given by Kasansky and Rice, has been derived from the difference of gravimetric and astronomic-geodetic deflections. The fact that Kasansky had only 82 gravity points, whereas Rice had 40,000, seems to have no appreciable influence on the accuracy. Obviously the astronomical observations must be considered responsible for this. In other words: The gravimetric deflections are almost as good as the elaborate astronomic-geodetic ones.

The present program of the Columbus Group is mainly to continue, systematize, and extend these practical applications. The work of Rice shows that we now have entered a new era of gravimetric exploration where the number of observations is rapidly increasing hundred- and thousandfold. Since the present nets are intended for local explorations, the situation favors the deflection computations, but the world-wide reconnaissance net of gravity anomalies is increasing too. The anomaly map of Tanni still shows vast blank areas which now are beginning to be filled, especially in North and South America, Africa, Australia, and the Pacific. In Russia there are many more observations than we have been able to collect at present because they usually are published only at long intervals. The other countries generally furnish us with their results immediately, even before publication. Some oil companies, especially the Gulf Research and Development Company, have also been very generous in promising us their gravity data.

The program also includes some theoretical discussions as to the most appropriate method of reduction, the most convenient formulas and tables for computing the long distances, etc. There is much work to be done, and we are lookkng forward to being aided by the best consultants and a competent staff for analyzing the material. The financial side of the program will be settled too.

At the assembly of the International Union of Geodesy and Geophysics in Brussels last August, this program was presented by Prof. Heiskanen. In its official resolution the Union "recognised with great satisfaction the establishment of this program and, strongly approving its objects, considered it necessary that close collaboration should be maintained with the individuals and institutions most concerned." This means that our work has received the approval and encouragement of the world's leading authorities in the field.

CONTRIBUTORS

THOMAS A. ELKINS

THOMAS A. ELKINS received his B.S. degree in 1927 and an M.S. degree in 1931 from Carnegie Institute of Technology. He has been connected with the Gulf Research & Development Company since 1930, with the exception of a period of study at Princeton University, from which he received an A.M. degree in mathematics in 1935. Mr. Elkins has devoted his attention primarily to mathematical and statistical problems of geophysical interpretation, particularly of gravity and magnetic data. He is a member of the American Geophysical Union, the American Mathematical Society, the American Physical Society, the American Statistical Association, the Institute of Mathematical Statistics, and the Society of Exploration Geophysicists.

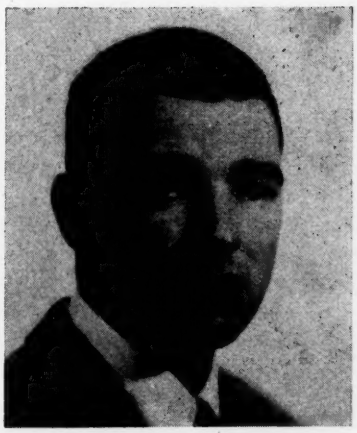
G. M. HABBERJAM

G. M. HABBERJAM graduated in Physics at Leeds University in 1947 and has since been engaged in geophysical research in the Mining Department of that University. He received the Ph.D. degree at Leeds in 1950. In 1949 he was appointed Research Assistant in Mining Geophysics, and in 1950 he became Assistant Lecturer in Surveying.

JULIAN HAWES

JULIAN HAWES was graduated from the University of Arkansas in 1934 with the B.S. in Geology. He did graduate work at the Universities of Oklahoma and Wisconsin, and Harvard University. He received the M.A. and Ph.D. degrees in Geology from Harvard. From 1938 to 1942 he was engaged in seismic and gravity exploration for The California Company and the Mott-Smith Corporation. Service in the United States Navy from 1942 to 1946 included sixteen months' work with the group engaged in perfecting the field use of the air magnetometer. Since 1946 he has been with the Stanolind Oil and Gas Company.

Dr. Hawes is a member of the American Association of Petroleum Geologists and the Society of Exploration Geophysicists. Scholastic society memberships include Phi Beta Kappa, Pi Mu Epsilon, Sigma Gamma Epsilon, and Sigma Xi (Associate).

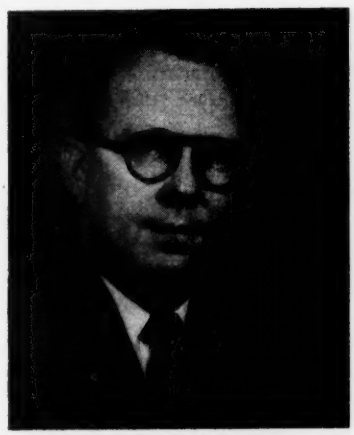


LEONARD V. LOMBARDI

LEONARD V. LOMBARDI entered Yale University in 1941 and received the B.S. in Geology in 1946, after serving two years in the United States Marine Corps. In 1949 he received an M.S. in Geology from Stanford University, and is now writing a dissertation for a Ph.D. in Geology, with the major field of Geophysics, at Stanford University.

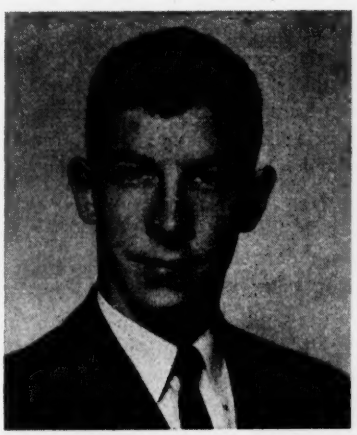
In 1950 he became a member of the Geophysics and Geology staff of Stanford Research Institute, where he now holds the position of Research Geophysicist.

He is an associate member of the Society of Exploration Geophysicists, the American Association of Petroleum Geologists, and Sigma Xi.



E. V. MCCOLLUM

E. V. MCCOLLUM received his A.B. degree in 1925 and his M.S. degree in 1926, both from the University of Oklahoma. He was employed by the Marland Oil Company from June, 1926, until July, 1929, and by Continental Oil Company as control geophysicist from July, 1929, until May, 1939. He was employed by the Mott-Smith Corporation as chief geophysicist from May, 1939, until September, 1943. Since 1943 he has been associated with E. V. McCollum and Company, gravity and magnetic contractors. He is a member of the American Physical Society, the American Geophysical Union, the Seismological Society of America, and the Society of Exploration Geophysicists. He served as Secretary-Treasurer of the Society of Exploration Geophysicists for the year 1948–1949.



GEORGE R. ROGERS

GEORGE R. ROGERS was born March 18, 1923 in Keokuk, Iowa. He entered the Colorado School of Mines in 1941. From 1943 to 1946 he served in the United States Navy, during which time he completed two semesters of undergraduate work at Doane College and eighteen months sea duty as Assistant Navigator aboard the U. S. S. *Tucson*. Upon the termination of the war Mr. Rogers returned to the Colorado School of Mines, graduating in 1948 with the degree of Geological Engineer in the Geophysics Option.

In 1948 Mr. Rogers joined the geophysical research department of Phelps Dodge Corporation at their western office in Douglas, Arizona, and is with that group at the present time. He is concerned with mining applications of geophysics with emphasis on electrical, magnetic, and gravity methods.

EDWARD V. SOMMERS

EDWARD V. SOMMERS received his B.S. degree in Metallurgy in 1939 from the Pennsylvania State College. He was employed by the Carnegie-Illinois Steel Corporation from 1939–1940 and by the Westinghouse Electric Corporation from 1940–1946 as a metallurgical engineer. In 1947, he was transferred to the physics section of the Research Division of Westinghouse and was employed there until January, 1951, when he joined the Field Research Laboratories of the Magnolia Petroleum Company where he is currently working on theoretical aspects of geophysical exploration problems. From 1943 to 1949 he attended evening sessions at the University of Pittsburgh and obtained his M.S. and Ph.D. degrees in mathematics in 1946 and 1949, respectively.

JOHN T. WHETTON is a graduate of the University of Leeds, and is a Master of Science of Leeds University and of Durham University, in England. At present he is Professor of Mining at the University of Leeds.

Professor Whetton has had practical mining experience in Great Britain, West and East Europe, and South America. He holds the First Class Colliery Manager's Certificate, is Greenwell Medalist of the North of England, and is a member of the Institute of Mining and Mechanical Engineers. He is the author of papers on prospecting, boring, sinking, methods of working, winding, and geophysical surveying.

He commanded the Fourth Survey Regiment, Royal Artillery, in the Middle East, Southeast Europe, and Western Europe during World War II. He is a member of the Distinguished Service Order, the Order of the British Empire, and holder of the Military Cross.

JOHN T. WHETTON

W. JACQUE YOST

W. JACQUE YOST was born in Fairview, West Virginia and received the B.A. degree in Mathematics and the B.S. degree in Physics from Furman University in 1935 and 1936, respectively. From 1936 to 1938 he was a Graduate Assistant in the Physics Department of Syracuse University from which he received his M.A. in 1938. He was University Fellow at Brown University from 1938 until 1940 at which time he received his Ph.D. degree in Theoretical Physics. He was on the physics faculty of Syracuse University in 1940 and 1941. He came to the Magnolia Field Research Laboratories as their first physicist in September of 1941. From that date until 1946 he was in charge of their research activities in Chemical Physics. In 1946 he transferred to the geophysical research division of the same laboratory in which division he is now working. He has been engaged in various research projects concerning the mathematical phases of geophysical interpretation.

He is a former member of the American Optical Society and a charter member of the American Society for X-Ray and Electronic Diffraction. He is a member of the Society of Exploration Geophysicists, American Physical Society, The American Geophysical Union, Dallas Geophysical Society, and Sigma Xi.

C. W. ZIMMERMAN

C. W. ZIMMERMAN was born in Oklahoma City, Oklahoma, in 1921. He received the B.S. degree in Electrical Engineering from the University of Oklahoma in 1943. Prior to graduation he was employed in the transformer design section of the Westinghouse Electric Corporation and as a special instructor at the University of Oklahoma. During the period from 1943 to 1946 he served as a radar officer with the U. S. Army Signal Corps. Following this, he was employed as an engineer in the long lines department of the American Telephone and Telegraph Company. Since 1948 he has been engaged as a research engineer at Magnolia Petroleum Company's Field Research Laboratories working on the development of new borehole logging techniques.

Mr. Zimmerman is a member of Tau Beta Pi, Eta Kappa Nu, Phi Eta Sigma, and the Institute of Radio Engineers.

SOCIETY ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the society. This publication does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the president within thirty days. Names of the references appear in parentheses after the name of each nominee.

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Robert V. Smith (Tom Edrington, James Walker, Richard Brewer)
Harry Robert Stenson, Jr. (L. F. Guseman, S. P. Weatherby, R. W. Upshaw)
Calvin Dean Stewart (E. J. Handley, R. G. DeGood, D. K. Davis)
Daniel Henry Sullivan (H. R. Prescott, B. G. Swan, B. J. Boring)
Norman Eugene Thompson (H. C. McCarver, R. A. Stehr, M. C. Kelsey)
William Ansel Thompson (W. R. Fillippone, C. B. Forbes, Wayne Denning)
Edouard Paul-Emile van der Linden, Jr. (E. J. P. van der Linden, A. A. Fitch, E. B. Lindsey)
Charles Joe Ward (P. H. Ledyard, Sidon Harris, R. H. Dana)

Edward Bassett Wasson (R. F. Beers, I. H. Cram, J. A. Harris)
Richard Lee Watson (Dean Walling, B. B. Strange, Aart de Jong)
Fred Welcker (Frank Ittner, C. E. Reel, D. E. Turner)
Herbert Clayton Wells (C. B. Forbes, W. R. Fillippone, W. H. Denning)
Jack Calvin Weyand (Sidney Schafer, J. D. Marr, T. F. Dupont)
Arthur Finus Whatley (B. B. Strange, Aart de Jong, R. W. Carter)
William Martin Young (E. J. P. van der Linden, A. A. Fitch)
Enrique Hector Yramategui (P. P. Conrad, W. L. Fellows, R. G. Couch)

TRANSFER TO ACTIVE

Joseph Edward Barthelemy, Jr. (Henry Salvatori, Harris Cox, Fred DiGiulio)
Jean Dienesch (H. B. Peacock, C. H. Green, L. Migaux)
William Glass Hazen (L. J. Peters, Sigmund Hammer, W. C. Lamb)
Henry Schoellhorn III (A. J. Barthelmes, H. M. Thralls, J. E. Hawkins)
James Ernest Thompson (T. H. Tillman, G. M. Conklin, W. E. Hollingsworth)
Garland Edward Tilley (S. B. Stewart, Donald Crary, R. F. Bennett)
James Ivan Walton (R. W. Gemmer, D. P. Carlton, J. P. Garner)
Dexter Earl Williams (V. J. Hunzicker, W. L. Moore, Homer Roberts)

TRANSFER TO ASSOCIATE

Neal Whitman Burr (O. B. Jackson, L.F. Uhrig, M. H. McKinsey)
Earl Lester Cummins (H. R. Prescott, L. E. Whitehead, B. G. Swan)
Lawrence E. Reilly (C. J. Donnally, G. O. Shettle, J. B. Macelwane)

PAPERS PRESENTED AT THE TECHNICAL SESSIONS OF THE EASTERN REGIONAL MEETING, MELLON INSTITUTE, PITTSBURGH, PENNSYLVANIA OCTOBER 25, 1951

Deep-Well Pressure Geophone.

THOMAS BARDEEN, Gulf Research & Development Company, Pittsburgh, Pennsylvania.

A new-type pressure-equalized deep-well geophone which responds to changes in pressure has been developed and tested. A rigid chamber containing a fluid considerably more compressible than the well fluid is elastically connected to the well fluid by a flexible diaphragm. A description of the detector is given. Results of field tests comparing this geophone with conventional geophones are shown. The pressure-type geophone gives sharper arrivals and has a better signal-to-noise ratio so that less explosive is needed.

Deep Sea Refraction Techniques and Measurements in the Atlantic Ocean.

MAURICE EWING, CHARLES B. OFFICER, PAUL C. WUENSCHEL, BRUCE C. HEEZEN AND GEORGE SUTTON, Lamont Geological Observatory (Columbia University), Palisades, New York.

During the Summer of 1950 and the Spring of 1951 refraction cruises were made by the members of the Lamont Geological Observatory on the research vessels *Atlantis* and *Caryn* of the Woods Hole Oceanographic Institute. A total of one hundred and three refraction stations were made in the Western Atlantic and Caribbean on these cruises. On all the deep water stations (>1000 fathoms) a determination of basement velocity and depth was obtained, and in all cases the basement had a velocity corresponding to the intermediate layer of earthquake seismology. About a third of the profiles were carried out far enough to locate the Mohorovicic discontinuity and determine the velocity of Pn. These results are discussed in detail elsewhere.

A description is given of the two ship deep sea refraction operation. The equipment, the reason

for its design, and what it accomplishes are discussed as well as the hydrophone handling and shooting technique.

Up-Hole Times.

J. P. Woods, The Atlantic Refining Company, Dallas, Texas.

The up-hole travel time for the seismic impulse from a dynamite explosion is usually taken to depend only on charge depth and formation velocity. In practice, this travel time is influenced by charge size, by filter setting, by instrument sensitivity and by previous history of the shot hole. In some areas, there occur anomalous up-hole times which are difficult to explain.

Microwave Shoran.

Frank C. Alexander, Jr., Gulf Research & Development Company, Pittsburgh, Pennsylvania.

The shoran radiolocation system may be used to obtain the position data required for making geophysical maps from airborne surveys.

The original VHF shoran will be briefly reviewed. The conversion to 3,000-megacycle operation will be described.

Field operation and maintenance will be discussed.

Natural Radiocarbon Measurement of Geologic Samples.

J. Laurence Kulp, Lamont Geological Observatory (Columbia University), Palisades, New York.

New developments in the technique of measuring natural radiocarbon 14 will be presented. Results on samples of geological interest provide quantitative data on rates of sedimentation and late Pleistocene chronology. A possible use of natural radiocarbon in oil prospecting will be suggested.

Caprock Thickness Interpretation from Gravimeter Survey on Moss Bluff Dome, Liberty and Chambers Counties, Texas.

Sigmund Hammer, Gulf Research & Development Company, Pittsburgh, Pennsylvania.

This paper reports a new interpretative technique for calculating a detailed caprock thickness map from the results of a special gravimeter survey over the shallow caprock area of a salt dome. The technique includes continuation of the surface gravity data down to the depth of the caprock. A few wells which had been drilled through the caprock into salt on the top of the dome were used to

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DELEGATES TO THE EASTERN REGIONAL MEETING TOUR LABORATORIES OF THE GULF RESEARCH AND DEVELOPMENT COMPANY

On October 26, 1951, geophysicists attending the Eastern Regional Meeting were guests of the Gulf Research & Development Co. on a tour of their laboratories at Harmerville, Pa. One of the four groups is shown in the top picture observing a demonstration by Dr. C. W. Tittle. *Left to right*, they are: D. K. Kirk, guide for the group (sorry, we didn't get the name of the second man), Dr. Tittle, J. H. Buehner, G. H. Westby, C. W. Donnelly, P. M. Konkel, E. V. McCollum, Sigmund Hammer, George H. Hazen (behind Dr. Hammer), Castle J. C. Harvey, B. Perkins, Jr., Albert J. Z. Caan, and Victor Vacquier. *Below*, the group looks on as Dr. J. W. Earley explains the molecular arrangement of clay minerals to Mr. Westby and Dr. Hammer. After luncheon at the Cafeteria of Gulf Research & Development Co., the delegates returned by bus to Pittsburgh for a complete tour of the Mellon Institute of Industrial Research.

CLAY STUDY

fix density values to yield the correct total caprock thickness. The calculated caprock thickness map shows many local features to guide core drilling to evaluate the mineral prospects of the caprock.

RELATION OF SEISMIC CORRECTIONS TO SURFACE GEOLOGY

H. M. THRALLS AND R. W. MOSSMAN, Seismograph Service Corporation, Tulsa, Oklahoma.

The arbitrary application of any set type of near-surface corrections to seismic data can lead to erroneous results. The determination of the type of correction to be used must be based, in part, on the type of formations present in the near-surface. Case studies are offered to illustrate various conditions, including use of "floating" elevation reference planes as compared to a constant datum or a base-of-shot reference.

Quality of Geophysical Measurements.

E. V. MCCOLLUM, E. V. McCollum & Company, Tulsa, Oklahoma.

The quality of geophysical measurements may be obtained from statistical studies in which the probable error is estimated. A method is presented to show how the approximate value of the probable error in reduced quantities may be derived. Application of the method to seismic, magnetic, gravity and other measurements is discussed.

The Geophysical Discovery and Development of the Bayou Couba Dome.

L. F. MELCHIOR, Gulf Research & Development Company, Pittsburgh, Pennsylvania.

This case history of the Bayou Couba Dome, St. Charles Parish, Louisiana reports the results of the geophysical exploration leading to discovery of the dome and discusses and compares the results of additional exploration, done to define the dome, with the actual dome shape determined from drilling.

Simultaneous Gamma-Ray and Neutron Logging.

GILBERT SWIFT, Well Surveys, Inc., Tulsa, Oklahoma.

Newly developed instrumentation for Radioactivity Well Logging is described, whereby two curves, the Gamma-Ray Curve and the Neutron Curve are made simultaneously, together with a record of the casing collar positions, on one upward passage of the logging instrument. A functional description of all of the system elements is provided, showing how the resulting log is continuously drawn in the surface vehicle on a multi-pen recorder, with consequent saving in rig-time and elimination of possible depth discrepancy between curves, which may exist where successive runs are required. The application of radioactivity logs to production problems is briefly reviewed.

Sedimentation, Stratigraphy and Geophysics.

W. C. KRUMBEIN, Northwestern University, Evanston, Illinois.

Geophysicists have long recognized that the stratigraphic section in any area is an important factor in geophysical exploration. Until relatively recently, sedimentary petrologists and stratigraphers have not had methods for expressing their geological data in the precise manner required for integration with geophysical findings. The recent rapid rise of regional stratigraphic analysis, based upon development of new mapping methods, permits quantitative evaluation of sedimentary and stratigraphic variables. From such evaluation it is possible to use geophysical data to help interpret geology beyond tested areas, and to use geological data to help evaluate unexplained geophysical anomalies.

The present paper emphasizes some of the principles of sedimentation and stratigraphy which need reexamination in terms of their relation to geophysical data. Problems of correlation, by geophysical methods, of facies prediction from velocity data, of better interpretation of geophysical findings in terms of sedimentary environment and tectonism, are developed with the aid of examples and illustrations.

FIFTH ANNUAL MIDWESTERN MEETING
BAKER HOTEL, DALLAS, TEXAS
NOVEMBER 19–20, 1951

The Fifth Annual Midwestern Meeting was sponsored by the Ark-La-Tex Geophysical Society, the Dallas Geophysical Society, the Fort Worth Geophysical Society, the Permian Basin Geophysical Society, and the Geophysical Society of Tulsa, with the Tulsa society acting as host.

Attendance at the meeting reached a new high with 1090 registrations, including 596 members and 494 non-members. A geographical breakdown of registrations follows:

Dallas 272, Houston 144, Fort Worth 80, Midland 79, San Antonio 23, Wichita Falls 21, Beaumont 15, Lubbock 12, Abilene 9, other Texas 101, total Texas 756. Tulsa 125, Oklahoma City 35, Ardmore 11, Bartlesville 10, Ponca City 7, other Oklahoma 15, total Oklahoma 203.

Shreveport 24, other Louisiana 12, total Louisiana 36. New Mexico 20, California 15, Pennsylvania 11, Colorado 9, Missouri 5, Nebraska 3, Wyoming 3. Illinois, Minnesota, North Dakota, Montana, Ohio, two each. Connecticut, Mississippi, Arkansas, New York, one each. Canada 6, Mexico 2.

Of the registrants, 580 were from the home cities of the sponsoring societies.

A cocktail party was held from 5 to 7 on Monday evening, and it is believed that every registrant was present. A dance was held in the Crystal Ballroom of the Baker from 9 to 12 Monday evening followed by a midnight breakfast; 467 attended.

The opening address of the technical session was made by Dr. B. B. Weatherby. A résumé of his address follows.

Our problem is to keep the country supplied with oil and gas. The 1952 production of crude oil is estimated to exceed two billion barrels, and world demand will probably increase by 35% over the next ten years. The immensity of the job of supplying the rising demands stands out sharply when we realize that in spite of the large size of Alberta's known reserves, they add up to about six months of United States consumption. Considerable seismic effort is maintained in old producing areas which have been shot from 20 to 50 times. If emphasis is to be placed on larger discoveries, crews should be moved out of these areas into more hazardous but potentially more profitable provinces which are relatively undeveloped. In the absence of a new prospecting tool of demonstrated ability to make significant contributions to our reserves, we must make more efficient use of existing seismic methods and crews. Differences in excess of 70% in coverage costs occur between two crews operating in the same area under essentially the same conditions with the more economical crew obtaining by far the best records. Many old instruments are still in use and should be replaced. Operators should be trained to get the most out of their instruments and field techniques. Poor first breaks, improper use of suppressors and expanders, and poor choice of filters often impair record quality, as also does failure to adapt field procedures to local problems. Use of excessive powder charges, short spreads, and failure to use spot correlations when possible lead to uneconomical use of the seismic tool. Careful interpretation through exhaustion of the seismic records at all levels is of course very important in determining the effectiveness of a seismic program. Data should not be pushed too far or it may be misleading. Velocity changes must be accounted for in making structural maps. Seismic data must be restudied as new subsurface information becomes available. Most weaknesses in instrument operation, field procedure, and handling of data are due to inadequately trained personnel. When supervisors, party chiefs, computors, and observers understand their part and carry it out thoroughly, we will be meeting the challenge of finding two billion barrels of oil a year most effectively.

Abstracts of the other papers appeared in the program, and are reproduced in this issue.

A rather lively discussion followed the paper by W. C. Pritchett on the Attenuation of Radio Frequency Waves through the Earth. Mr. Wm. Barret read a prepared discussion in which he deplored the small scale size of the experiment stating that the data were not from the region of the radiation field. Barret quoted excerpts from letters by J. H. Stratton, C. A. Heiland, and Lee de Forrest which expressed the opinion that the distances used by Pritchett were too small for an adequate test of the Barret Radoil prospecting method. Dr. McGeehee presented a written discussion

with slides. Utilizing Pritchett's data, wave lengths of 27.6, 31, and 46.7 feet were computed. McGeehee stated that this puts the region of Pritchett's experimentation in the zone intermediate between the near zone of induction field (0.1 λ) and the far zone of radiation field (10 λ). Mr. H. A. Morris described experiments in which the transmitter and receiver were placed in mud-filled trenches. The radiation field in the air and earth were observed and calculated. Potential probes were used in determining the earth field. Morris considered that the antenna system included the mud in which the aerials were imbedded. His data followed the shape of Pritchett's curves but extended a greater distance. Replying to a question by W. T. Born as to whether distance was the crucial point, Morris mentioned interference pattern due to the "intermediate region" of the experiments. Replying to Pritchett, Morris stated he did not measure earth resistivity. Answering Wyckoff's question on source of interference, Morris said the antenna was considered as a "double-cone" system created by combination of aerial and liquid, and gave a 1949 text as reference. H. L. Scharon then cited the discovery of a lead body by radio method as a reason for extending distance. Scharon suggested that radio wave technique is in the same state as the resistivity method 20 years ago, and that classical theory may be inadequate. Also he suggested necessity for many experiments in various subject areas and geological formations.

KARL DYK
General Chairman,
PROGRAM AND ARRANGEMENTS

Tulsa, Oklahoma
November 29, 1951

PAPERS PRESENTED OR READ BY TITLE AT THE TECHNICAL SESSIONS OF THE FIFTH ANNUAL MIDWESTERN MEETING BAKER HOTEL, DALLAS, TEXAS NOVEMBER 19–20, 1951

*Opening of Meeting.**

R. W. GEMMER, President of Geophysical Society of Tulsa. The Carter Oil Company, Tulsa, Oklahoma.

The Geophysical Society of Tulsa, the Dallas Geophysical Society, the Ark-La-Tex Geophysical Society, the Ft. Worth Geophysical Society, and our newest member, the Permian Basin Geophysical Society, with headquarters at Midland, welcome you to the Fifth Annual Midwestern Meeting of the Society of Exploration Geophysicists.

We wish to emphasize that this welcome is extended not only to members of the various geophysical societies but to geologists and others interested in the oil industry. Geophysics, the youngster of the oil industry, is approaching maturity. We not only have recovered from childish exaggerated ideas of our importance but also from our failures that were the natural result of our early enthusiasm. Geophysics is no longer considered a replacement for any exploration method but has fitted in as a working member of the oil-finding fraternity. It is for this reason that we are particularly glad to have others in the oil industry attend our meeting. We want the constructive criticism of our elders in our discussions with the hope that by working together we can together increase the reserves available to this country.

Although the Tulsa society is the official host for this meeting we wish to point out that the meeting is the result of the efforts of all five societies. It simply fell to the lot of the Geophysical Society of Tulsa to act as the leader in preparing this meeting.

Now speaking mainly to geophysicists, I wish to say that we have the best job I know of. We don't work, we play. We play a game. Our opponent in the game is nature used in the broad sense. Nature makes oil and hides that oil in the ground. Some of it is easy to find so that even with a slight amount of understanding of the game we have some reward. We make some score. A game that is too easy, however, is no fun. The game has to stay above our level of understanding to remain inter-

* The entire text of Mr. Gemmer's address is presented.

esting. The game of checkers, I am told, practically disappeared when the mathematicians reached a complete understanding of it. If in our game with nature we were successful 100 percent of the time, the game would lose its interest and our work would become routine. We are admittedly a long ways from this point. Now the fun in any game that we have not mastered is to be a little better at it than anybody else. A good bridge player studies the game; he reads books on the subject; he talks it with people in whom he recognizes ability and, as a result, becomes a better player, and in the geophysical game this is the purpose of our meeting. It is an opportunity to talk and listen to those who have been successful in various phases of the game we are playing. Now, we as individuals can attend the meetings, enter into the discussions and become better players, or we can waste our time while here by dozing through the papers, entertaining our friends in our rooms, or visiting the various attractions available to visitors in Dallas. To me, these meetings are an opportunity, and for them to be a success we need to work harder here than we would at home. In two short days most of the known experience in the geophysical art is going to be laid on the table for us to look at. Whether we become better players depends on us alone.

Remarks by the President.

SIGMUND HAMMER, President of S.E.G. Gulf Research & Development Company, Pittsburgh, Pennsylvania.

Opening Address—Some Uses and Abuses of the Seismic Method.

B. B. WEATHERBY, Amerada Petroleum Corporation, Tulsa, Oklahoma.

Exploring for Pennsylvanian Reefs in the Permian Basin with the Reflection Seismograph.

SIDON HARRIS, Southern Geophysical Company, Inc., Fort Worth, Texas.

General remarks concerning the use of the reflection seismograph in locating Pennsylvanian Reef deposits in the Pre-Permian Section of the Permian Basin are made with some illustrations, including seismograms and cross sections. Special consideration is given to the Wellman Field of Southern Terry County discovered in 1950 by the Anderson-Prichard Oil Corporation. Several important steps or necessary criteria are listed with reference to the detection and recognition of possible Pennsylvanian Reef build-ups.

Geophysical Exploration in the San Juan Basin.

NEAL CLAYTON, Century Geophysical Corporation, Tulsa, Oklahoma.

A general discussion of the problems encountered in making geophysical surveys in the San Juan Basin. Magnetometer and gravity surveys are complicated by the extreme topographic relief and the presence of Tertiary intrusives. Seismic surveys are hindered by the scarcity of water for drilling. Housing for all geophysical crews is a major problem. Adequate velocity and well control are lacking in most parts of the basin.

Geophysical History of the Golden Trend of Oklahoma.

JOHN R. HILL, The Carter Oil Company, Oklahoma City, Oklahoma.

Until the discovery of oil in the Deese (Pennsylvanian) formation in the Globe-Vickers #1 Gibson, SE NE 30–3N-2W, in February 1946, exploration for oil west of the Nemaha Ridge in Oklahoma had been directed primarily toward location of simple anticlines and fault closures. Discovery of Deese oil in an area which had been thoroughly detailed by seismograph throughout a period of more than ten years, and which had showed no structural folding from reliable seismic data, immediately indicated the possibility for widespread stratigraphically trapped oil.

Maps, both new and old, were studied in a new light. Isopachous maps were constructed from seismograph data which reflected the Deese pinch-out. All wells throughout the province were carefully checked for Deese sand thicknesses and shows of oil and water. The seismic maps, particularly the isopachs, were coordinated with these Deese sand studies and a resultant outline drawn which

was believed to encompass the Deese oil possibilities. The result is considered a good example of the benefits of closely coordinating geology and geophysics.

The recommended outlines based on the wedgeout of the Deese from seismic cross-sections and isopachous maps, although insufficient in many places and too extensive in others, served as a substantial guide for acquiring productive acreage.

Relation of Seismic Corrections to Surface Geology.

H. M. THRALLS AND R. W. MOSSMAN, Seismograph Service Corporation, Tulsa, Oklahoma.

The arbitrary application of any set type of near-surface corrections to seismic data can lead to erroneous results. The determination of the type of correction to be used must be based, in part, on the type of formations present in the near-surface. Case studies are offered to illustrate various conditions, including use of "floating" elevation reference planes as compared to a constant datum or a base-of-shot reference.

Quality of Geophysical Measurements.

E. V. MCCOLLUM, E. V. McCollum & Company, Tulsa, Oklahoma.

The quality of geophysical measurements may be obtained from statistical studies in which the probable error is estimated. A method is presented to show how the approximate value of the probable error in reduced quantities may be derived. Application of the method to seismic, magnetic, gravity, and other measurements is discussed.

S.E.G. Project Regarding Microcarding of Geophysical Literature.

MILTON B. DOBRIN, Magnolia Petroleum Company, Dallas, Texas.

Early last spring the Dallas Geophysical Society voted some of its surplus funds for the purpose of building up the collection of geophysical literature at the Fondren Library of Southern Methodist University. This was felt to be a particularly useful project for the Society on account of the large number of important geophysical journals, particularly foreign ones, which are not obtainable anywhere in the Dallas area. A rapid expansion in recent years of geophysical activity in this vicinity has made the need for easily accessible reference material of this type particularly urgent.

When the committee administering the project began to inquire where it could obtain complete back files of the various journals it wanted for the collection, it immediately ran into difficulties. Nearly all the publications on its list were out-of-print and not to be found in the catalogues of any of the firms dealing in second-hand scientific literature. Those few back files that could be located were generally incomplete and exhorbitantly priced.

When the committee learned, about this time, that the S.E.G. was putting out-of-print back numbers of *Geophysics* on microcards, it seemed possible that other journals might be reproduced in this form for the Dallas collection. The matter was taken up with Mr. Fremont Ryder, head of the Microcard Foundation, a non-profit group promoting use of this medium for duplicating out-of-print literature. According to Mr. Ryder, it would not be economically feasible to put out anything on microcards at all unless at least fifteen copies were printed and sold of each item. In the case of the geophysical journals, however, the Foundation would only require a minimum guarantee of ten sales before it would undertake to microcard a publication, since it would count on selling the other five itself. With this number printed, the sale price would run from one-third to one-half cent per original page.

Although the Dallas Geophysical Society could, of course, only agree to buy one set of cards for each journal, it seemed likely that libraries elsewhere, particularly those of universities, oil companies and geophysical companies, might be glad of an opportunity to purchase these back files this cheaply, even if not in their original form. Other cities where there is a concentration of geophysical activity seem to be about as badly off as Dallas as far as accessibility to the literature is concerned. In view of the expanded scope of the proposed microcarding project, the Dallas group suggested to the S.E.G. executive committee that the National Society look into its feasibility. A committee was accordingly

appointed by Dr. Hammer to investigate the matter. It consists of R. A. Geyer, Carl Bryan, and the writer, who is chairman.

For those who are not familiar with microcards, it may be appropriate to point out here that they are simply 3×5 inch cards coated with an especially fine-grained emulsion on which a standard-size page can be reduced to the size of a shirt button without loss of definition. This card has sixty-two journal pages printed on it and costs only about twenty cents. It is read with a special projecting machine which blows each page up to original size or larger on a ground-glass screen. This model reader costs $120.00.

The Committee has made a list of twelve geophysical journals (see Table) which from the standpoint of importance and present accessibility would be most likely to be in demand among geophysicists. The price estimates are tentative and are for a minimum printing of fifteen sets of cards. The number of volumes gives an idea of the amount of material involved in each complete file. Some of the journals go back into the last century.

Estimated Prices on Journals in Microcarded Form

Title of Journal	*No. of Volumes*	*Estimated Price*
Zeitschrift für Geophysik	14	$36.00
Monthly Notices of The Royal Astronomical Society, Geophysical Supplement	6	14.00
Bulletin of the Earthquake Research Institute, Tokyo (in English)	23	58.00
Beiträge zur Angewandten Geophysik (Gerlands)	10	22.00
Terrestrial Magnetism and Electricity (Since 1949, Journal of Geophysical Research)	53	74.00
Japanese Journal of Astronomy and Geophysics (in English)	20	28.00
Gerlands Beiträge zur Geophysik	42	84.00
Geophysical Magazine, Tokyo	11	22.00
Annali di Geofisica (Ital.)	3	7.00
Annales de Géophysique (Fr.)	7	7.00
Geofisica Pura et Applicata (Ital.)	16	16.00
Transactions, American Geophysical Union	31	73.00
Total		$441.00

The committee is about to canvass a large number of reference libraries as well as certain oil companies and contract geophysical companies to determine how much demand there is for the various journals on this list. We are sending out questionnaires to more than 100 such organizations and on the basis of the interest shown by the replies, the executive committee can decide whether, and to what extent, the microcarding project should be carried through.

The Committee hopes that any members of the Society who would like to have these publications available in their own communities or within their own companies, will bring this proposition to the attention of those persons handling purchases for their libraries. Perhaps some of the other local geophysical societies might find it possible to sponsor the purchase of microcarded geophysical literature in their own areas. We feel that the Society, by making this material widely available at a low cost, can offer a most valuable service to its membership.

Geology of the Permian Salt in the Western Anadarko Basin, Kansas-Oklahoma.

D. F. Moore, Stanolind Oil & Gas Company, Wichita, Kansas.

Coincident with abrupt and rather large seismic velocity changes in parts of the Western Anadarko Basin is the presence of two distinct Permian salt basins. The margins of these basins have been fairly well defined. Major salt development occurs immediately below the Blaine and indicates as much as 350 feet of divergence in the Blaine-Cimarron interval. Present topographic expressions indicate that percolating ground waters and subsequent solution phenomena have been active since at least Late Pliocene time.

Primarily, this paper will discuss the Permian stratigraphy as related to the seismologists' prob-

lem; relative structural movements; theory of salt origin and removal thereof by solution-collapse phenomena.

Salt Solution, a Seismic Velocity Problem in Western Anadarko Basin, Kansas-Oklahoma-Texas.

M. B. WIDESS, Stanolind Oil & Gas Company, Tulsa, Oklahoma.

Solution of salt from a shallow Upper Permian formation in parts of Western Anadarko Basin was observed to produce a profound and relatively abrupt velocity change, such as to cause over 300 feet of seismic relief error across a distance of less than three miles. Core-hole velocity shooting and velocity profiling were used in the study of the effect of salt solution. The theory, methods, and results of the velocity profiling program are described. The core-hole velocity data are analyzed relative to several shallow velocity zones, the evidence suggesting that the velocity has been altered by more than one stage of ground water activity.

Development of a New Method of Seismic Velocity Determination.

F. P. KOKESH, Schlumberger Well Surveying Corporation, Jackson, Mississippi.

Considerable interest has recently been aroused in a new method for measuring seismic velocities wherein the explosive charge is placed in the hole and the seismic energy is picked up with detectors placed on the surface. Experimentation carried on during the past year indicates that the new method is quite workable.

This paper attempts to outline the basic problem of velocities and their measurement and describes the preliminary development that has been done thus far on the new method of velocity measurement.

Deep-Well Pressure Geophone.

THOMAS BARDEEN, Gulf Research & Development Company, Pittsburgh, Pennsylvania.

A new-type pressure-equalized deep-well geophone which responds to changes in pressure has been developed and tested. A rigid chamber containing a fluid considerably more compressible than the well fluid is elastically connected to the well fluid by a flexible diaphragm. A description of the detector is given. Results of field tests comparing this geophone with conventional geophones are shown. The pressure-type geophone gives sharper arrivals and has a better signal-to-noise ratio so that less explosive is needed.

Up-Hole Times

J. P. WOODS, The Atlantic Refining Company, Dallas, Texas.

The up-hole travel time for the seismic impulse from a dynamite explosion is usually taken to depend only on charge depth and formation velocity. In practice, this travel time is influenced by charge size, by filter setting, by instrument sensitivity, and by previous history of the shot hole. In some areas, there occur anomalous up-hole times which are difficult to explain.

Surface Damages Incurred in Oil and Gas Leasehold Development and Geophysical Operations.

TOM SEALY, Stubbeman, McRae and Sealy, Midland, Texas.

The subject will encompass nature of surface and mineral estates, their relationship to each other and reasonable use of the surface for development of the mineral estate, nature of the granting clause in oil and gas leases, conflicting usages of the surface in mineral development, liability only for damages resulting from acts of negligence, good faith trespass, use of airborne equipment and recommendations for better co-operation between surface owners and geophysical operators.

Near-Surface Seismic Waves in a Part of the Edwards Plateau, Texas.

THOMAS C. POULTER AND LEONARD V. LOMBARDI, Stanford Research Institute, Stanford, California.

Extraneous energies, frequently repetitive and sufficiently strong to mask completely any reflections, appeared very prominently on a set of seismic records obtained in Crockett County, Texas. These energies consist of several cycles showing large stepouts, and are presumably the results of horizontally traveling near-surface waves.

In an attempt to discover the source of these energies, a group of records was obtained with varied shot point offsets and recording spread orientations. The evidence deduced from analysis of these records, and means of reducing the effects of the disturbances are discussed.

Geology of the Williston Basin.

W. M. Laird, North Dakota Geological Survey, Grand Forks, North Dakota.

The Williston Basin covers about two-thirds of North Dakota, overlapping into South Dakota, Montana, Manitoba, and Saskatchewan. In North Dakota about 14,000 feet of sediments have been deposited in the deepest part of the basin. Of these sediments, about 10,000 feet can be considered to contain potential oil-bearing strata. Discoveries of oil and gas have been made in two horizons of the Devonian and one horizon in the Mississippian. In all 37 wells have been drilled or are drilling in search of oil or gas. In addition to these, there are 27 wells which have been drilled for shallow gas mostly in the Eagle sand of the Pierre shale in the southwestern part of the state.

Rocks of all systems of the Paleozoic are apparently present although rocks of the Pennsylvanian and Permian are found only in the southwestern part of the state. All periods of the Mesozoic are present but of the Cenozoic only the Paleocene, Eocene and Oligocene and Pleistocene are recognized.

The general structure outline of the basin can be shown by contours on the Dakota sandstone. It should be noted that this basin has been progressively sinking throughout geologic time. Within the confines of the basin are a number of known folds, the largest of which is the Nesson anticline. The origin of these folds is unknown. Some probably owe their origin to orogenic forces but some smaller folds may be due to compaction.

The most important exploration method now being used is the seismograph although other geophysical instruments and surface geology are not being neglected. More drilling is needed to evaluate which exploratory tool or tools are best. Probably it will be found that all tools must be used together.

Exploration Problems of the Williston Basin.

K. E. Burg, Geophysical Service Inc., Dallas, Texas.

The various types of structures to be encountered in the Williston Basin and the application of the seismograph and other geophysical tools to the location of these structures will be discussed.

Specific examples in the form of seismograph record cross sections will be used to show the ability of the reflection seismograph to locate these structures. Many of the unique problems encountered in the area will be illustrated and suggested solutions will be outlined.

Continuous Velocity Logging.

G. C. Summers and R. A. Broding, Magnolia Petroleum Company, Dallas, Texas.

A method for obtaining a continuous well log of formation acoustic compressional velocity is described. The instrument is composed of an acoustic pulse generator separated from a receiver by a five-foot acoustic insulator. Means are provided for generating an acoustic pulse and automatically selecting and recording the first break travel time as detected by the receiver. The instrument has a range of 5,000 to 25,000 feet per second and an accuracy better than 5 percent. The log is taken in a conventional well logging manner at speeds of 100 to 150 feet per minute. In addition to the travel time the amplitude of the received pulse is also recorded.

Typical logs are illustrated along with their correlation to seismic reflection horizons and lithology in the borehole.

Seismic Velocity Logging.

W. D. Mounce, C. L. Hubbard, C. J. Charske and H. P. Kuppers, Humble Oil & Refining Company, Houston, Texas.

An instrument containing a sound source and a pair of receivers is described which measures the time required for a pulse to travel vertically one foot through the earth. These travel times are recorded at the surface at a rate of about ten per second as the instrument is moved continuously through a bore hole. Examples of logs made in several different geologic provinces are given, and comparisons with other logs and with cores are shown.

Preliminary Comparison of Velocities Obtained by Delta Time Analysis and Well Velocity Surveys.

B. G. SWAN AND ADRIAN A. BECKER, Continental Oil Company, Ponca City, Oklahoma.

The relative accuracy of velocities obtained from time-delta time analysis as compared with well velocity surveys is demonstrated by comparison of time-depth curves. Reflection spreads used in the t-delta t analyses were grouped as closely as possible around the wells to reduce the effect of lateral velocity changes. The results of using varying numbers of spreads are given and some of the other factors involved are discussed.

Studies of a Surface Seismic Disturbance.

J. D. Eisler, Stanolind Oil & Gas Company, Tulsa, Oklahoma.

Seismic studies in a caliche covered area revealed the existence of a prominent surface wave group. The dispersive characteristics of this wave group and the existence of retrograde elliptical particle motion place it in a class of Rayleigh waves. Examples of vertical as well as two-component motion are presented.

Surface Wave Studies under Various Conditions of Near-Surface Lithology.

MILTON B. DOBRIN AND PHILIP L. LAWRENCE, Magnolia Petroleum Company, Dallas, Texas.

During the past several years an experimental seismic crew of the Magnolia Petroleum Company has been studying surface waves and other disturbances commonly designated as "ground roll" in areas having a variety of near-surface lithologic conditions. One objective of these studies is to be able to explain, and eventually predict, the characteristics of the various waves in terms of the elastic properties of the layers near the surface. Experiments have been carried on at locations where the surface material is clay, sand, weathered shale, and hard limestone. Logs were made of compressional and shear velocities to specify the elastic characteristics in the uppermost hundred feet or so of the section.

Records made with close geophone spacing using wide band (5–200 cps) recording equipment and three-component registration show that ground roll generally consists of three kinds of traveling waves: (1) compressional waves multiply refracted along near-surface boundaries, (2) shear waves refracted and reflected in the shallow layers, and (3) Rayleigh waves. Of these, the Rayleigh waves are most conspicuous and cover the greatest portion of the records.

The velocities and periods of the Rayleigh waves depend mainly on the thickness and elastic properties of the surface layer as well as on the elastic characteristics of the subjacent material. Where there is a low-speed weathered layer, the propagation is dispersive and the velocity-period relations can be predicted approximately if the distribution of near-surface compressional and shear velocities is known. Where the surface layer has a higher speed than the substratum, the Rayleigh waves are observed as pulses rather than trains, as would be predicted by theory. Where the surface material is loose sand, the Rayleigh waves are highly irregular and difficult to correlate with theory.

Sample record arrays from various areas in East Texas having these different types of surface lithology will be shown to illustrate these relationships.

Geological History of the Denver-Julesburg Basin.

ALEX W. MCCOY, III, Gulf Oil Corporation, Tulsa, Oklahoma.

The gross sediments of the Denver Basin from Cambrian through Cretaceous are discussed. Isopachous maps are presented. From these the tectonic history of the Denver Basin is reviewed and its structural development is reconstructed.

Seismic Exploration of the Denver-Julesburg Basin.

B. F. RUMMERFIELD, Century Geophysical Corporation, Tulsa, Oklahoma.

Recent developments in northeastern Colorado and southwestern Nebraska have resulted in a marked increase in seismic activity within the Denver-Julesburg Basin.

The low relief of many of the sub-surface structures, coupled with the extraneous effects of weathered zone, elevation changes, surface deposits and velocity variation taxes the resolving power of the seismic method and the interpretative ability of the geophysicist.

Attenuation of Radio Frequency Waves through the Earth.

W. C. PRTCHETT, The Atlantic Refining Company, Dallas, Texas.

Evidence has been presented by several investigators indicating the possibility that radio waves penetrate sufficiently deep into the earth to be useful in prospecting for oil.

Conventional electromagnetic theory used with normal values of the earth constants indicates, however, that the attenuation is too great to allow the signal to be used after propagation through significant distances of shale.

To settle the above question an experiment was conceived and carried out in which the signal level in the earth was measured at various distances from a battery-operated transmitter operating at 1,652 kc suspended in an uncased, mud-filled hole by a mud-saturated rope. The mud resistivity was matched to that of the 40 foot thick shale section used in order that the entire immediate region would be as nearly as possible homogeneous. The receiver was also battery-operated and suspended by a cable in other similar mud-filled holes at various distances from the first hole.

The attenuation constant in shale was found to be .18 nepers/foot (1.56 db/foot), which is much too large to give any hope of deep penetration. A few measurements in a limestone section gave a value of .086 nepers/foot, which is also too large to be useful. Although these values are quite high, they are lower than theory predicts for these earth resistivities by a factor of about three.

Elevation Survey by Single Altimeter.

JOHN M. CRAWFORD, Continental Oil Company, Ponca City, Oklahoma.

Presents a rapid and inexpensive method for locating errors in elevation of seismograph shot points by means of a single altimeter and observer. A simple system of field notes enables the observer to differentiate between atmospheric irregularities, errors in reading the altimeter and errors in the original survey.

Isochron Analysis of Seismic Data.

E. D. ALCOCK, National Geophysical Company, Inc., Dallas, Texas.

This paper endeavors to point out a criterion for the location of oil reservoirs, which, while not new, has not been used extensively in seismic exploration to date. This criterion is based upon the postulate that associated with every oil reservoir there is an anomalous change in the seismic section. By anomalous is mean either an increase or decrease of time interval between any two seismic reflecting horizons, both of which lie above the reservoir or between two, one lying above and the other below the reservoir. Several examples will be shown of seismic data analyzed with the Isochron Technique.

Geophysical Methods in Exploration for Gold Deposits in the Witwatersrand System in the Union of South Africa.

OSCAR WEISS, Weiss Geophysical Corporation, New York City, New York.

In South Africa, gold is found primarily within conglomerates of the Upper Witwatersrand System, about 10,000 feet thick, which consists mainly of quartzites and non-magnetic shales. The density of the quartzites is about 2.6 g/cm^3. This series is underlain by the 10,000 ft. thick Lower Witwatersrand System containing highly magnetic shales with a density of about 2.8. Overlying the Upper Witwatersrand are non-magnetic Ventersdorp lavas and dolomites, with density about 2.8,

which extend to the surface. Thus, any area in which the Upper Witwatersrand conglomerates are relatively shallow should show positive magnetic and negative gravity anomalies.

Since 1934, magnetic and gravity surveys have been carried on over the Northern Orange Free State and the southern portion of the Western Transvaal in an effort to locate new gold fields. Drill tests are run where magnetic anomalies show the Lower Witwatersrand beds to be relatively shallow and negative gravity anomalies also occur, indicating the possibility of gold bearing formations in the Upper Witwatersrand.

The program has led to the discovery of 24 actual or potential gold mines in the West Witwatersrand , Orange Free State and Stilfontein areas. Present valuation of these properties is around $6,000,000,000.

Seismic reflection and refraction methods have also been tried, but have not been successful.

Geophysical Exploration in Cuba.

F. K. Fisk, Exploration Surveys, Inc., Dallas, Texas.

Columbus reported the presence of asphalt in Cuba in 1492. Small amounts of oil have been produced since 1881. The north coastal area of Cuba has been extensively explored by drilling and by geophysical methods with little success. The south coastal area contains a number of geophysical anomalies which have not been tested. It appears at present that the key to production in the southern area lies in the correlation of gravity and magnetic data with subsurface information as obtained from drilling.

ANNOUNCEMENT OF ANNUAL JOINT MEETING, S.E.G., A.A.P.G. AND S.E.P.M. BILTMORE, HOTEL, LOS ANGELES, CALIFORNIA

March 24–27, 1952

Society of Exploration Geophysicists
Executive Committee

Sigmund Hammer, President
George E. Wagoner, Past President
Curtis H. Johnson, Vice President
Robert C. Dunlap, Jr., Secretary-Treasurer
Paul L. Lyons, Editor

American Association of Petroleum Geologists
Executive Committee

Frank A. Morgan, President
Clarence L. Moody, Past President
Lewis G. Weeks, Vice President
Robert H. Dott, Secretary-Treasurer
Kenneth K. Landes, Editor

Society of Economic Paleontologists and Mineralogists
Council

Thomas H. Philpott, President
W. C. Krumbein, Past President
K. O. Emery, Vice President
Cecil G. Lalicker, Secretary-Treasurer
Jack L. Hough, Managing Editor

S.E.G. Pacific Coast Section
Officers

Wallace L. Matjasic, President
David H. Scott, Southern Vice President
Robert B. Galeski, Northern Vice President
Maurice Sklar, Secretary-Treasurer

A.A.P.G. Pacific Section
Officers

Homer J. Steiny, President
Harold H. Sullwold, Jr., Vice President
Rufus M. Smith, Secretary-Treasurer

S.E.P.M. Pacific Section
Officers

W. T. Rothwell, President
James L. Cowell, Secretary-Treasurer

Convention Arrangements

Howard C. Pyle (A.A.P.G.)
Joint General Chairman

Sam Stewart (A.A.P.G.)
Joint General Vice Chairman

Curtis H. Johnson
S.E.G. General Chairman

Furman A. Grimm
S.E.G. General Vice Chairman

Kenneth O. Emery
S.E.P.M. General Chairman

Committee Chairmen

Technical Program

Curtis H. Johnson, Chairman for S.E.G.
Leo R. Newfarmer, Chairman for A.A.P.G.
Kenneth O. Emery, Chairman for S.E.P.M.

Field Trips

Theodor H. Braun, Chairman for S.E.G.
Frank Parker, Chairman for A.A.P.G.
Orville Bandy, Chairman for S.E.P.M.

Hotels and Housing

Sam Grinsfelder (A.A.P.G.), Chairman
E. L. Erickson (S.E.G.)
Louis Simon (S.E.P.M.)

Registration

Roy M. Barnes (A.A.P.G.), Chairman
Frank Ittner (S.E.G.)
Herschel Driver (S.E.P.M.)

Publicity

Richard Sneddon (A.A.P.G.), Chairman
Dale Turner (S.E.G.)

Finance

J. R. Pemberton (A.A.P.G.)

Entertainment

Stanlus Z. Natcher (A.A.P.G.)

Transportation

Homer J. Steiny (A.A.P.G.)

Exhibits

Joe B. Hudson (A.A.P.G. and S.E.G.)

S.E.P.M. Luncheon

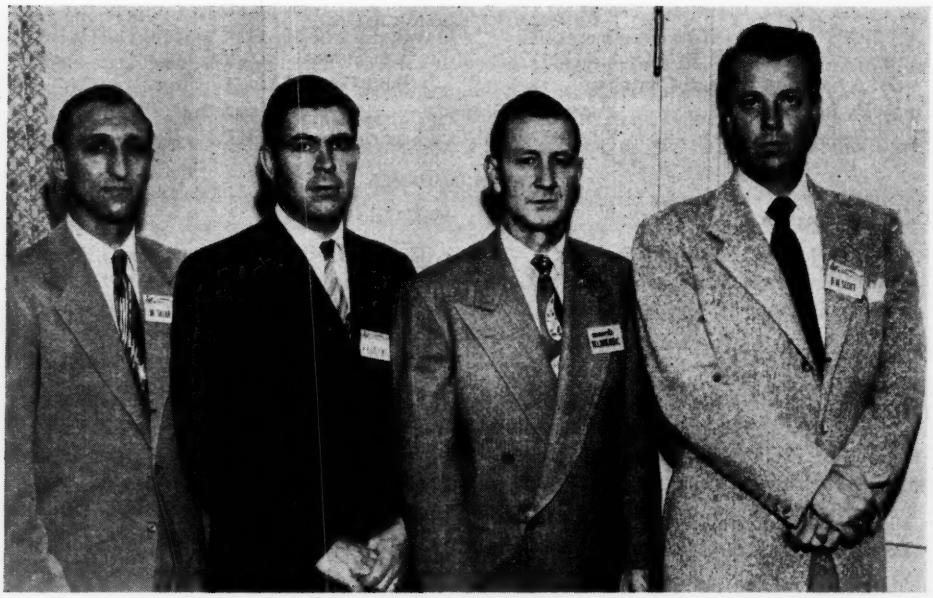
Aden Hughes (S.E.P.M.)

Public Address and Projection Equipment
Bart W. Sorge (A.A.P.G. and S.E.G.)

ANNOUNCEMENT

The 22nd Annual Meeting of the Society of Exploration Geophysicists will be held at the Biltmore Hotel, Los Angeles, California, on March 24–27, 1952. As in previous years, this meeting will be held jointly with the annual meetings of the A.A.P.G. and the S.E.P.M. Thus, the 37th Annual Meeting of the American Association of Petroleum Geologists will be held on March 24–27 and the 26th Annual Meeting of the Society of Economic Paleontologists and Mineralogists will be held on March 25–27.

In general, the schedule of events will follow the custom of previous years. Registration will begin Sunday morning, March 23rd in the Galeria of the Biltmore Hotel, and S.E.G. members are particularly urged to register Sunday if at all possible. Monday, March 24th, there will be a full-day session of the S.E.G., including the business meeting first thing Monday afternoon. The A.A.P.G. and the S.E.P.M. have each planned a Los Angeles Basin Field Trip for Monday. Monday evening the A.A.P.G. has tentatively planned an illustrated talk on Australian Coral Reefs and the S.E.G. is sponsoring a short meeting open to all interested in safety and accident prevention. Tuesday is the joint-session day of presidential addresses, distinguished speakers, presentation of honors and special papers of common interest to the three societies. Tuesday evening the S.E.G. Council will meet. On Wednesday, the three societies will meet in separate full-day sessions, with an A.A.P.G. research symposium and panel discussion tentatively scheduled for Wednesday evening. Thursday, the S.E.G. will hold a technical session in the morning and a field trip in the afternoon, while the A.A.P.G. and the S.E.P.M. will again meet in full-day separate sessions. The convention will close on Thursday evening with the



PACIFIC COAST SECTION ELECTS OFFICERS

At the annual Fall Meeting of the Pacific Coast Section, S.E.G., on November 1 and 2, 1951, new officers of the Section were elected. In the picture above they are, *left to right:* Maurice Sklar, Secretary-Treasurer; R. B. Galeski, Vice President Northern District; W. L. Matjasic, President; and D. H. Scott, Vice President Southern District.

annual joint dinner-dance and floor-show. There will be two post-convention field trips by the A.A.-P.G.

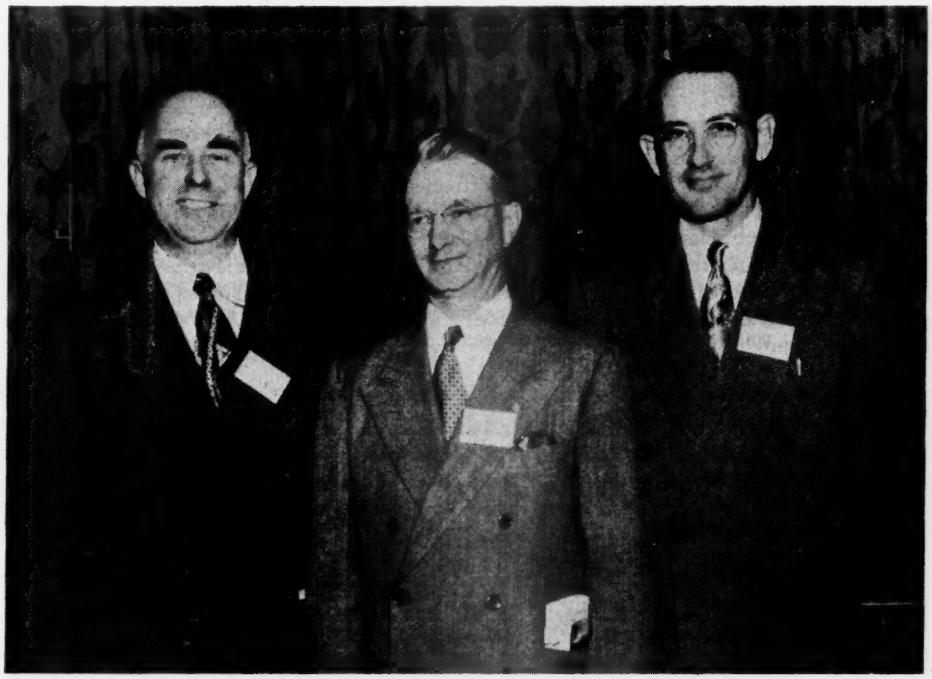
TECHNICAL PROGRAM

Since the A.A.P.G. and S.E.P.M. do not schedule technical sessions on Monday, March 24th, the S.E.G. plans to present geophysical papers of general interest at its all-day Monday session, in addition to a short business meeting featuring reports by officers of the society and chairmen of standing committees. Among the Monday papers will be case histories of fields, and exploration techniques and results in basins of current interest. Tuesday, at the joint session with the A.A.P.G. and the S.E.P.M., Dr. Sigmund Hammer, President of the Society of Exploration Geophysicists, will give an address. It is contemplated that a second S.E.G. speaker will discuss offshore geophysical exploration while an A.A.P.G. and S.E.P.M. speaker will each discuss offshore topics in their fields. Wednesday morning the S.E.G. will present a symposium on geophysical exploration for stratigraphic traps, to be followed in the afternoon by papers on instrumental and interpretative techniques. Thursday morning, a symposium on mining geophysics will be offered for the first time since the joint annual meeting in 1948.

Program chairman for the S.E.G. is its Vice President, Curtis H. Johnson. The personnel of the Program Committee, representing all local sections, and regions where no local sections exist, has been published in *Geophysics*, beginning with the July, 1951, issue. Some local sections have formed special program committees to plan local programs and these committees deserve much credit for pre-viewing and forwarding many excellent papers for the annual meeting in Los Angeles.

A.A.P.G. Technical Program

The A.A.P.G. Program Committee, under the chairmanship of Leo R. Newfarmer, has organized



EXPLORATION SCIENTISTS ATTEND PACIFIC COAST MEETING

Pictured above, *left to right*, are: Curtis H. Johnson, Vice President of the S.E.G.; Sigmund Hammer, President of the S.E.G.; and K. O. Emery, Vice President of the Society of Economic Paleontologists and Mineralogists. The national exploration society officials were guests of the Pacific Coast sections of the S.E.P.M., A.A.P.G., and S.E.G. during the annual joint meeting November 1 and 2, 1951, in Los Angeles.

a well-rounded program in addition to its contributions to the joint session on Tuesday. The A.A.P.G. "kick-off" takes place Monday evening with a talk both educational and entertaining. Tentative arrangements feature Dr. Curt Teichert, Geological School, University of Melbourne, presenting "Australian Coral Reefs" with colored pictures. Wednesday will be devoted to fundamental papers and the beginning of the research symposium which is tentatively scheduled to be concluded in an evening session Wednesday. The Thursday session will feature papers of regional or basin significance throughout the Western Hemisphere.

S.E.P.M. Technical Program

In addition to a presidential address and a paper relating to offshore studies, in the joint session on Tuesday, the S.E.P.M. will feature a symposium on "Objectives in Modern Sedimentology" and a probable second symposium on "Recent Marine Sedimentation" in its Wednesday and Thursday technical sessions. Kenneth O. Emery, Vice President of S.E.P.M., is program chariman.

FIELD TRIPS

S.E.G. Field Trip

Thursday afternoon, March 27, a field trip to the California Institute of Technology and the new offices and laboratory of the United Geophysical Company in Pasadena has been scheduled. Busses will leave the Biltmore at 1:00 P.M., and again at 2:00 P.M., and will return to the Biltmore not later than 5:00 P.M. so that participants will have plenty of time to prepare for the dinner-dance Thursday

evening. Theodor H. Braun is the S.E.G. field trip chairman. Questionnaires regarding participation in the field trip should be returned promptly to Mr. Braun.

A.A.P.G. Field Trips

Monday, March 24, a Los Angeles Basin field trip has been scheduled by the A.A.P.G. which will include visits to the Los Angeles and Long Beach Harbor areas. A choice of two post-convention field trips is offered: a one-day trip on Friday north along the coast to San Louis Obispo, returning via Bakersfield and the south end of the San Joaquin Valley; and a two-day trip north along the coast to San Francisco, returning via the San Jaoquin Valley. The A.A.P.G. field trip chairman is Frank Parker. Questionnaires regarding the A.A.P.G., S.E.P.M., and S.E.G. field trips have been sent by Mr. Parker to all A.A.P.G. and S.E.P.M. members and should be returned promptly to him. S.E.G. members will recieve their questionnaires from Mr. Braun, as noted above, and should return them promptly to him.

S.E.P.M. Field Trip

The S.E.P.M. field trip to San Pedro and Palos Verdes Hills in the Los Angeles Basin will be held on Monday, March 24th. It will include visits to type localities of several well-known formations which have excellent microfauna. Dr. Orville Bandy is field trip chairman and will lead the excursion.

ENTERTAINMENT

Stanlus Z. Natcher is chairman of the committee for entertainment. In addition to the dinner-dance and floor-show on Thursday night, March 27, the entertainment committee is engaged in plans for "California Style" entertainment for the visiting ladies.

EXHIBITS

The Biltmore Hotel will have space available for exhibits as it has in the past. Prospective exhibitors are being contacted by the exhibits chairman, Joe B. Hudson.

ROOM RESERVATIONS

The form for requesting hotel room reservations has been mailed to each member and it is urged there be no delay in returning the reservation form, If any member has not received the form, he may request another from society headquarters. Because of the limited number of single rooms available, there will be a much better chance of securing the desired accommodations if the request calls for rooms to be occupied by two or more persons, All reservations must be cleared through the housing committee, which is headed by Sam Grinsfelder. All requests for hotel rooms should be made by returning the form to the Joint A.A.P.G., S.E.G., and S.E.P.M. Housing Committee, Attention Mr. Sam Grinsfelder, Chairman, Room 1102, 617 West Seventh Street, Los Angeles 17, California. Requests for reservations should be made as far in advance of February 20, 1952, as possible, and should contain all information requested. Receipt of requests will be acknowledged and filed in order of receipt by the housing committee. Actual assignments will be made in the various hotels and confirmations will be mailed about sixty days prior to the convention. Members who request reservation but later find they cannot attend should notify the housing committee without delay. Blocks of rooms will not be reserved and all rooms must be reserved in the names of individuals.

ANNUAL GULF COAST MEETING

May 29 and 30, 1952

Dates have been set by the Houston Section for a two-day meeting on May 29 and 30, 1952, at the Rice Hotel in Houston, Texas. Although the complete plans of the meeting have not been formulated, this announcement is made for the benefit of those companies and individuals who wish to

schedule the attendance of their personnel in advance. An official notice will be mailed to all members of the society well in advance of the meeting.

Eugene W. Frowe, of Robert H. Ray Company, and Vice President of the Houston Section, is in charge of program and arrangements.

SIXTH ANNUAL MIDWESTERN MEETING

November 13 and 14, 1952

The Ark-La-Tex Geophysical Society, Shreveport, La., has chosen November 13 and 14, 1952, as the dates of the next annual Midwestern Meeting. The Shreveport Section will act as host, and the meeting will be held at the Texas Hotel in Fort Worth, Texas. Assisting in plans for the meeting will be the Dallas, Fort Worth, Midland, and Tulsa Sections of the S.E.G. Official announcement will be mailed to all members of the society well in advance. Members are requested to notify the management of their respective companies at this time to assist in planning their attendance.

REPORT ON PUBLICATION OF GEOPHYSICAL CASE HISTORIES VOLUME II

This is the report of the Special Committee on Publishing Volume II of Geophysical Case Histories. President Hammer appointed this committee by letter dated June 8, 1951, in line with a motion passed by the Council at the annual meeting in St. Louis in April, 1951.

The committee and all with whom we discussed the matter are unanimously in favor of publishing Volume II. It may be recalled that Volume I was intended to be the first of several.

Our first volume has well fulfilled its purpose. It has benefited the Society and the exploration branch of the oil industry in many ways. Universities and colleges are using it to good advantage as a text book and for a reference book. Among the oil and gas companies it is a valuable reference volume for management, geologists, geophysicists and other company personnel.

In the first three years the Society has sold over 2,400 copies of Volume I. A similar number remain, sales continue, all volumes are paid for, a substantial net income has been of material aid to the Society, and an additional net amount will be forthcoming.

There are between ten and fifteen case history papers ready for Volume II. A total of around fifty to sixty will be needed. We estimate it will take between one and two years to publish the new volume.

It should be easier to obtain papers now since all interested have benefited from the first volume, and no anticipated troubles have developed.

We recommend appointment of a relatively large committee, similar to that which produced Volume I. If each company having material for case histories in its files would contribute two, the new volume could be published in about a year.

The inclusion of mining case history papers as well as additional foreign ones is desirable. We also believe it important to include more subsurface geology, where available, in order to emphasize the interrelation of geophysics and geology in the solution of exploration problems.

We recommend a strong, well-known member of the Society as chairman of the committee, as his duty will be to enthuse the other members in obtaining the necessary papers. The next annual meeting and all regional ones should feature case histories.

HENRY C. CORTES, *Chairman*
L. L. NETTLETON
PAUL L. LYONS

Dallas, Texas
October 31, 1951

PROPOSED AMENDMENTS TO THE BYLAWS

As requested in President Hammer's letters of June 6 and July 17, 1951, the Constitution and By Laws Committee has considered By Laws Article VII and Article X and recommends the following revisions:

The purpose of the first group of Amendments is to provide a more definite schedule for the nomi-

nation and election of officers. The purpose of the other group is to specify the manner of appointment and the duties of the recently added Standing Committees.

By Laws Article VII. For Sections 4, 5 and 6 substitute the following Sections 4, 5, 6, 7 and 8

Section 4. Prior to December 1, nominations in writing, signed by at least twenty Honorary Members or Active Members in good standing and accompanied by the written consent of the candidate, may be submitted to the President.

Section 5. Between December 1 and December 15, the Business Manager will prepare and mail to each member, eligible to vote, a ballot listing all candidates properly nominated for each office. The candidates shall be listed alphabetically. With each ballot, the Business Manager shall send an official envelope having the member's name on the back.

Section 6. The Standing Committee on Nominations shall appoint a Committee of Tellers to count the ballots.

Section 7. Each member voting may cast one vote for each officer and shall return his ballot to the Business Manager in the official envelope carrying on the outside the written signature of the member submitting the ballot. Only ballots so prepared by members in good standing, and received by the Business Manager at his officially recognized address not later than January 31 shall be valid.

Section 8. The Business Manager shall indicate which ballots are valid, and shall deliver all ballots unopened to the Tellers after February 1. The candidate receiving the greatest number of valid votes cast for an office shall be declared elected to that office. In case of a tie, the Standing Committee on Nominations shall decide by a secret vote which of the candidates shall be elected. Results of the mail ballot shall be communicated to all candidates by the Nominating Committee on or before February 15.

By Laws Article X. Revise Sections 3 and 4 to read:

Section 3. The Standing Committee on Nominations shall consist of the President who shall be chairman, the Past President, and Past Prior President. Its duties shall be to nominate candidates for officers, appoint Tellers to count the ballots and to declare the election of the officers as prescribed in Article VII of these By Laws.

Section 4. The Standing Committee on Membership shall consist of three active members appointed for a period of one year by the President immediately following the Annual Meeting. One of the members appointed shall have been a member the preceding year. The Committee shall prescribe the manner of soliciting applicants for membership and to recommend for membership any person considered by the Committee to be worthy thereof.

Add Sections 10 to 14 as follows:

Section 10. The Standing Committee on Distinguished Lectures shall consist of six active members appointed for three years by the President. The two senior members of the Committee shall retire after the Annual Meeting. The Chairman of the Committee shall be appointed for one year by the President. The Committee shall obtain Distinguished Lectureres in geophysics and plan and supervise tours by these Lectureres to the Local Sections of the Society and other participating organizations.

Section 11. The Standing Committee on Radio Facilities shall consist of from 5 to 15 active members appointed for one year by the President. The Committee shall, upon request from its Chairman, determine the opinions of the members of the geophysical industry concerning matters pertaining to the use of radio in geophysics.

Section 12. The Standing Committee on Reviews shall consist of from 5 to 10 members who need not be active members of the Society. The members and the Chairman shall serve a two year term concurrent with the editor and shall be appointed by the editor. The Committee shall prepare reviews of current geophysical literature for publication in *Geophysics*.

Section 13. The Standing Committee on Public Relations and Publicity shall consist of a Chairman, appointed for one year by the President, and such additional members, appointed for one year

by the Chairman, as he may deem desirable. The Committee shall advise the officers and council of the Society concerning matters pertaining to Public Relations and shall prepare and arrange for the distribution of suitable publicity material for the press and radio.

Section 14. The Standing Committee on Geophysical Activity shall consist of four or more active members of the Society appointed for a term of one year by the President. The Committee shall conduct an annual survey of geophysical activities throughout the world. This report shall be presented before the Society at its annual meeting and published in the July issue of *Geophysics*. It may be made available for publication in leading trade journals for release at the time of the annual meeting.

Constitution and By Laws Committee
W. M. Rust, Jr., *Chairman*

Houston, Texas
September 20, 1951

MIDLAND SECTION PUBLISHES MAP

The Permian Basin Geophysical Society, Midland, Texas, has recently completed a map (scale 1/500,000) showing wells which have been shot for velocity in West Texas, West Central Texas, Southeast New Mexico, and the Texas and Oklahoma panhandles.

The map is presented in two sections on ozalid paper. Each well has an index number by County (taken from the Permian Basin Geophysical Society publication, "Wells Shot for Velocity") with available survey depth and lowest formation surveyed.

Prices are as follows:

First copy (per company)	$15.00
Additional copies	7.50
Each additional half	5.00

Orders should be addressed to Permian Basin Geophysical Society, Box 1018, Midland, Texas. Payment must be sent with order; a receipt will be returned with the map.

NOMOGRAMS

It has been decided to publish regularly in *Geophysics* nomograms designed for the solution of common interpretive problems in geophysical work. Nomograms are solicted from members of the society and accredited geophysicists. To be acceptable, nomograms should be designed to conform, upon reduction, to the page size of *Geophysics*. They should be accompanied by a short mathematical explanation of the formula or formulae involved and of the construction of the nomograms. Explicit directions for their use should be clearly stated. Acceptance of nomograms will be at the discretion of the editor, referees, or the publications committee.

PRINT ORDER FOR 1952 *GEOPHYSICS* TO BE 4,400 COPIES

Effective this issue, the print order for *Geophysics* will be 4,400 copies of each issue. This will be an increase of 600 over the 1951 figure of 3,800 copies for each issue. The new figure includes distribution to 2,918 members and an anticipated 500 member increase, to 750 subscribers, and a 232 volume supply for back numbers demand.

PROPOSED FOREIGN EXCHANGE OF REPRINTS OF GEOPHYSICAL PAPERS

A recent letter from Prof. H. Haalck, Director of the Geodetic Institute in Potsdam, Germany to Dr. Sigmund Hammer proposes an exchange of reprints of geophysical papers with American authors. The exchange is designed partially to overcome the present difficulties in international distribution of technical periodicals.

Authors of papers are urged by Dr. Hammer to send reprints to interested persons in foreign countries. This should prove to be a very effective way to promote international good will and to broaden the influence of *Geophysics* in advancing the geophysical profession.

Geophysics will publish the names of those persons in foreign countries interested in such an exchange provided they state their interest by writing to the business manager of this society.

THE AMERICAN GEOLOGICAL INSTITUTE

During the last several months, the Institute has given particular attention to the problem of scientific manpower in general. The manpower problem is getting more and more difficult as is shown not only by the activities of the Institute itself but by other publications and organizations as reported in the Institute's *News Letter*. A recent number of the *Scientific American* was devoted entirely to various factors which have contributed to the current shortage of technical manpower. One factor which has not been generally appreciated is the very considerable effect of the low birth rate around twenty years ago, during the depression. The Engineers Joint Council and the Engineer's Society of Western Pennsylvania sponsored a meeting of some 500 engineers from 28 states in Pittsburgh in September to explain and discuss the current shortage of engineers and their role in the national economy. Speakers were high officials in large industrial companies and others prominent in the manpower field. The situation also has been reviewed in an article in the September, 1951, number of *Fortune* and reprints of this have been circulated by the Institute to its *News Letter* and other subscribers.

To promote knowledge of the Institute itself, wide distribution has been given to a pamphlet "This is Your Institute" which has been sent to the membership of several of the member societies, including the S.E.G. It is to be hoped that our membership has given this the attention it deserves and have come to a better understanding of what the Institute is and what it is trying to do.

Recent numbers of the Institute's *News Letter* have contained items of interest to S.E.G. members. For the July number, the guest editorial on "Geophysical Exploration Comes of Age" was prepared by the President of our Society. This reviews the history of the organization, its rapid growth and the economic place in the oil industry which geophysical exploration now has attained.

The August number contains a review of developments in geochemistry; this points out the application to mining exploration of chemical tests for various metals. Extremely sensitive tests have been devised which can be made with relatively simple and inexpensive portable field equipment and determinations can be made in the field making it unnecessary to ship samples to a central laboratory.

The September *News Letter* contains two items of geophysical interest. One on "Resistivity and Geological Interpretation," by M. Kamen-Kaye, points out geological uses of resistivity logs which are somewhat different from usual applications. The details of such logs have led to much better understanding of the processes of sedimentation and geological history in certain areas. For instance, in Venezuela, logs have shown the occurrence of silty phases in sand bodies and these have been interpreted as the result of cyclic changes in deposition with a period of the order of a thousand years. It is quite possible that careful use of information from electrical and radioactivity logs can lead to much better understanding of geological processes and paleogeography.

The same number reviews some work by the U. S. Geological Survey in the application of electronic depth finding equipment for mapping geological contacts under water. Under favorable conditions, the depth finding equipment gives a response not only from the bottom of the water but also from contacts at considerable depth below the bottom. This has been used successfully to map bed rock in advance of engineering construction, and has saved a great deal of core drilling. It would appear that, under suitable conditions, the electronic depth finder can accomplish such results more rapidly and economically than short range refraction seismograph or electrical surveys which had been applied to such problems.

The annual meeting of the Board of Directors of the Institute was held in Detroit on November 6 and 7, just before the G.S.A. meeting which began on November 8. The new officers elected at that are:

President: Carey Croneis, President, Beloit College.

Vice-President: Joseph L. Gillson, Geologist, E. I. DuPont de Nemours Co.

Secretary-Treasurer: Harry S. Ladd, Assistant Chief Geologist, U.S.G.S.

The selection of Dr. Croneis to lead the Institute at a time which may be a very critical one in the establishment of its position and influence is a particularly happy one. It is from the seeds planted in his inspiring talks, beginning nearly ten years ago,* that the present American Geological Institute has grown. His clear and well expressed ideas of the service which it can perform to deserve the support which it needs should go far to establish the Institute as a highly fruitful organization to serve the geological profession in fields which are much broader than those covered by any one of its constituent societies.

The financial committee, under Roger Dennison, reported fair progress in the solicitation of support for the Institute from industry which depends on geology. It is clear that there is still much misunderstanding of the functions of the Institute and its usefulness to the profession. Dr. Croneis is very hopeful that, when the institute is understood, it will be supported in the way that those who have been working with and for it believe it deserves.

The Publication Committee, J. V. Howell, Chairman, is starting to investigate means for reducing costs of publication of geological journals. The committee is undertaking the compilation and publication of glossary of geological terms. This is planned to be much more complete than anything of the kind now in existence. It will be compiled from existing published glossaries, many of which are appended to books in various geological fields and also from any privately compiled word lists. Each constituent society is naming a member to serve on a general steering committee and to head a committee within the society to select words from each field to be included. Dr. R. A. Geyer has accepted the appointment as the steering committee member from the S.E.G.

L. L. NETTLETON

EDITORIAL FROM *AGI NEWSLETTER* FOR JULY, 1951

Geophysical Exploration Comes of Age

This year (1951) is the twenty-first anniversary of the founding of the Society of Exploration Geophysicists. As the Society comes of age, it is of interest to take stock of its growth and accomplishments and of its future prospects.

The Society was organized in 1930 by a group of geologists and geophysicists in Houston, Texas, who recognized the need for interchange of ideas to develop and improve geophysical techniques in exploration for oil. The list of charter members includes 46 names, among them such well-known geologists as Alexander Deussen and Donald C. Barton Today the Society membership exceeds 2,700 in 41 states and 49 foreign countries. There are eight local sections and three student sections who hold monthly meetings to discuss important technical problems for the professional advancement of their members. Additional local sections, both in the United States and abroad, are in process of formation.

The scope of professional interest embraces all problems related to scientific exploration for mineral resources of all kinds in the earth's crust. The Society was first organized as the *Society of Economic Geophysicists*. A year later this was changed to *Society of Petroleum Geophysicists* and finally, five years later, to its present name, the *Society of Exploration Geophysicists*. The SEG is affiliated with the American Association of Petroleum Geologists and is a Member Society of the American Geological Institute.

* Carey Croneis, Geology in War and Peace, *A.A.P.G. Bull.*, Vol. XXVI, pp. 1221–49 (July 1942). Also geological "Union Now," discussion, *A.A.P.G. Bull.*, Vol. XXVII, pp. 1001–07 (July 1943).

The economic importance of geophysical exploration is clearly shown by its applications in the petroleum industry. Official SEG records show that over $200,000,000 were spent last year for geophysical explorations by the oil industry in the United States alone. The additional amounts spent for research in the improvement of present techniques and the development of new ones is not known but is undoubtedly several millions more. The commercial acceptance of geophysics is justified by its success. Lahee's well-known annual statistical analyses show that the success expectancy of a wildcat drilled in the hope of discovering a new oil field in the United States averaged, during the past five years, about 1 in 30 for non-technical selection of the drilling site (random drilling); 1 in 10 for geological basis; 1 in 6 for geophysical basis; and 1 in 5 for combined geological and geophysical basis. When we consider that the total expenditure for geophysics is only a little over 10% of the total cost of exploration for oil, these statistics take on additional significance.

As to the future, we have every reason to expect that geophysics will play an ever-increasing role in the discovery of mineral resources. It is obvious that the easiest fields to find are found first. Geophysics gives us the only methods now known for peering into the depths of the earth ahead of the drill to glimpse, however dimly, the minerals and conditions favorable for the accumulation of minerals under inches up to thousands of feet of rock cover.

SIGMUND HAMMER, *President*
Society of Exploration Geophysicists

PERSONAL ITEMS

JOSEPH A. SHARPE, vice president of Frost Geophysical Corporation since 1945, has been elected president of Frost Airborne Survey Corporation, with headquarters in Tulsa, Oklahoma. The new company, organized jointly by Aero Service Corporation of Philadelphia, Pa., and Frost Geophysical Corporation of Tulsa, is licensed, under certain basic patents issued to Gulf Research & Development Company of Pittsburgh, to perform aeromagnetic surveys for oil structures and minerals. Dr. Sharpe served as Editor of *Geophysics* from 1942 to 1945.

ERIK UNO GARPNER, 50, died recently at Los Angeles. Mr. Garpner joined the Society in 1946 as an active member. He had worked for the Dixie Oil Co., Stanolind Oil & Gas Co., Frost Geophysical Corp., Reed Magnetic Surveys, United Geophysical Co., and Seismograph Service Corp. His wife, Thelma Ethelny, and two sons, Erik Jan and Jan Alan Garpner, survive.

J. RIDGELY LEGGETT was recently named supervisor of the Montevideo, Uruguay, office of Exploration Surveys International, Inc. Mr. Leggett formerly was employed by the California Research Corp. as research engineer.

C. E. HENDRICKS, formerly a director and vice president in charge of engineering at Century Geophysical Corporation, has resigned to form his own organization for the maintenance, servicing and repair of seismograph instruments and as consultants for engineering problems related to seismology. The new firm will be known as the C. E. Hendricks Company, Tulsa, Oklahoma.

DON B. WINFREY has resigned as Rocky Mountain supervisor for the Petty Geophysical Engineering Co., and announces the organization of the Winfrey Exploration Company with headquarters in Casper, Wyoming, P. O. Box 755.

R. N. HARDING, geophysical supervisor for The Texas Company at Denver, Colorado, has been promoted to assistant to division manager, geophysical division of the producing department. Mr. Harding succeeds B. H. TREYBIG, JR., recently resigned, and will be located at Houston.

R. L. WALES, geophysical supervisor for The Texas Company at Calgary, Alberta, Canada, has been promoted to assistant to division manager, geophysical division of the producing department. He will remain in Calgary.

SIDON HARRIS, president of Southern Geophysical Company, announces the promotion of R. H. DANA from vice president to executive vice president; W. D. BAIRD, from treasurer and supervisor to vice president; and R. E. DAVIS, from supervisor to assistant vice president. Dana has been with Southern since the fall of 1945. He had been with Stanolind Oil & Gas Co. in the geophysical department since 1934, and is a graduate in geology from the University of Wisconsin. Baird has been with Southern since June, 1947, when he joined the Company in a supervisory capacity. He had been with Geophysical Service Inc. since 1933, after graduating in engineering from the University of Arkansas. Davis is now in charge of Southern's Permian Basin office in Midland, Texas.

B. H. TREYBIG, JR., announces the organization of the Louisiana Exploration Company, a seismic exploration contracting company, specializing in salt dome and fault problems common to Gulf Coast geophysics, with headquarters in New Iberia, Louisiana. Treybig attended Rice Institute and joined The Texas Company in 1932. He was geophysical supervisor for the Louisiana division from 1944 to 1950 and assistant to the geophysical division manager until his recent resignation.

R. A. GEYER, past Editor of *Geophysics*, and research geophysicist for Humble Oil & Refining Company, Houston, served as session leader during the Second Annual National Conference on Coastal Engineering held in Houston November 7–9, 1951. The subject of his session was "Engineering Problems and Data Determination."

R. L. FENTEM, seismic party chief for the Amerada Petroleum Corp., has transferred from Levelland to Brownfield, Texas.

J. T. RANDELL is now managing director of The Geophysical Prospecting Co., Limited, with offices at 39 Victoria Street, London, S.W. 1, England.

L. L. BRANTLEY, JR., formerly with Western Geophysical Co. at Peace River, Alberta, Canada, has joined Hudson's Bay Oil & Gas Company Ltd., 534A 8th Avenue West, Calgary, Alberta.

C. J. LOMAX has joined Continental Geophysical Company as supervisor. His company address is Box 9335, Fort Worth, Texas.

ROBERT G. MILLS, formerly with British-American Oil Co., is now geophysical supervisor for Precision Exploration Co., 409 Palace Building, Tulsa, Oklahoma.

LEE H. PRICE is now employed by Geophysical Service Inc., 6000 Lemmon Avenue, Dallas 9, Texas.

JOHN SLOAT, formerly at Bakersfield, is now with the Union Oil Company's Los Angeles office, Union Oil Building, Los Angeles 17, California.

W. O. BAZHAW, C. D. ROEMER, AND JAMES R. NEW announce the formation of Consolidated Geophysical Surveys, specializing in gravity surveys and interpretation, radioactive surveys, and photographic surveying equipment. Offices of the new company are located at 211 Boulder Building, 19 West Tenth Street, Tulsa 14, Oklahoma.

PAUL L. LYONS, Editor of *Geophysics*, has resigned as staff geologist with The Carter Oil Company to accept the position of exploration manager for Anchor Petroleum Company.

RICHARD A. GEYER, research geophysicist of the Humble Oil and Refining Co., has accepted appointment as a representative of the SEG on the Publications Committee of the American Geological Institute. Mr. Geyer was Editor of *Geophysics* from 1949 to 1951.

DAVID B. CAMPBELL, 51, supervisor with Independent Exploration Co., Fort Worth, Texas, died en route to a hospital after suffering a heart attack at Meadowbrook Municipal golf course at Fort Worth. A native of Butler, Pa., Mr. Campbell had been with the company for 16 years. He became a member of the SEG in 1936.

ELMER F. BLAKE is in charge of the newly opened Denver division office of Southern Geophysical Co., and will be in charge of the company's Rocky Mountain operations. His office is located at 504 Denver Theater Building.

CLEM A. DAHSE is with Stanolind Oil and Gas Co. at 308 9th Ave. West, Calgary, Alberta, Canada.

G. O. SHETTLE, formerly of Post, Texas, may now be addressed in care of the Mayes-Bevan Company at 305 Kennedy Building, Tulsa 3, Oklahoma.

R. A. HARTENBERGER of Phillips Petroleum Company, has transferred from Lamesa, Texas to Box 2138, Pampa, Texas.

A. E. MCKAY announces a change in the mailing address of Continental Geophysical Company to Box 9368, Fort Worth, Texas. The Company's offices are located at 6100 Camp Bowie Boulevard, Fort Worth.

R. G. ELMS, Union Sulphur and Oil Corporation, is now located at 663 Gulf Building, Houston 2, Texas.

A. GARCIA ROJAS, of Petroleos Mexicanos, is now located at Montes Urales 785, Lomas de Chapultepec, Mexico, D. F.

W. S. WALLIS, of Pacific Western Oil Corporation, has returned from Kuwait, Persian Gulf, and is now located at 1060 Subway Terminal Building, 417 South Hill Street, Los Angeles 13, California.

PETER J. RUSCH and L. MOTA, both of United Geophysical Co., S. A., announce their new address at Caixa Postal 197, Natal, R.G.doN., Brazil.

JAMES R. PACE has resigned as computer for Geophysical Service Inc. to accept the position of geophysicist with British American Oil Co., Ltd., with offices at 209 6th Avenue West, Calgary, Alberta, Canada.

WILLIAM J. FENNESSY, exploration geophysicist with Humble Oil and Refining Company, has transferred from Houston, Texas, to Morgan City, Louisiana. He may be addressed in care of the company at Box 666, Morgan City.

GORDON R. BELL, district geologist for Western Gulf Oil Company, announces removal of his office from the Motta Building to 222 East Chapel Street, Santa Maria, California.

ROBERT L. KRETZ, geologist and geophysicist with Bell Petroleum Company, has moved his office from the Continental Building to 222 Midland Savings Building, Denver 2, Colorado.

CHARLES G. FABION, senior observer for The Atlantic Refining Company, has transferred from Big Lake, Texas, to Box 1226, Plainview, Texas.

DAVID J. STUART has resigned as airborne geophysicist with the United States Geological Survey and is now working on a seismic crew of Socony-Vacuum Oil Company, Apartado 246, Caracas, Venezuela.

O. A. STRANGE has resigned the position of supervisor for Western Geophysical Company at Casper, Wyoming, to become geophysicist for The Pure Oil Company, Box 271, Tulsa, Oklahoma.

JOHN M. LANKTON, owner, announces the new location of Mountain Seismic Company at Box 98, Aurora, Colorado.

M. A. CLEVENGER has advanced to the position of party chief for Geophysical Associates of Canada, 510 9th Avenue West, Calgary, Alberta, Canada.

STATEMENT OF THE OWNERSHIP, MANAGEMENT, CIRCULATION, ETC., REQUIRED BY THE ACTS OF CONGRESS OF AUGUST 24, 1912, AND MARCH 3, 1933 of GEOPHYSICS, published quarterly at Menasha, Wisconsin for January, 1952.

State of Oklahoma }
County of Tulsa } ss.

Before me, a Notary Public in and for the State and county aforesaid, personally appeared Colin C. Campbell, who, having been duly sworn according to law, deposes and says that he is the business manager of GEOPHYSICS, and that the following is, to the best of his knowledge and belief, a true statement of the ownership, management (and if a daily paper, the circulation , etc., of the aforesaid publication for the date shown in the above caption, required by the Act of August 24, 1912, as amended by the Act of March 3, 1933, embodied in section 537, Postal Laws and Regulations, printed on the reverse of this form, to wit:

1. That the names and addresses of the publisher, editor, managing editor, and business managers are: Publisher, Society of Exploration Geophysicists, Box 7248, Tulsa 18, Oklahoma; Editor, Paul L. Lyons, Box 801, Tulsa 2, Oklahoma; Business Manager, Colin C. Campbell, Box 7248, Tulsa 18, Oklahoma.

2. That the owner is Society of Exploration Geophysicists, Box 7248, Tulsa 18, Oklahoma; President: Sigmund Hammer, Drawer 2038, Pittsburgh 30, Pa.; Vice-President: Curtis H. Johnson, Box 2122, Terminal Annex, Los Angeles 54, Calif.; Secretary-Treasurer: R. C. Dunlap, Jr., 6000 Lemmon Ave., Dallas 9, Texas; Past President: Geo. E. Wagoner, Drawer 1739, Shreveport, La.

3. That the known bondholders, mortgagees, and other security holders owning or holding 1 per cent or more of total amount of bonds, mortgages, or other securities are: None.

4. That the two paragraphs next above, giving the names of the owners, stockholders, and security holders, if any, contain not only the list of stockholders and security holders as they appear upon the books of the company but also, in cases where the stockholder or security holder appears upon the books of the company as trustee or in any other fiduciary relation, the name of the person or corporation for whom such trustee is acting, is given; also that the said two paragraphs contain statements embracing affiant's full knowledge and belief as to the circumstances and conditions under which stockholders and security holders who do not appear upon the books of the company as trustees, hold stock and securities in a capacity other than that of a bona fide owner and this affiant has no reason to believe that any other person, association, or corporation has any interest direct or indirect in the said stock, bonds, or other securities than as so stated by him.

5. That the average number of copies of each issue of this publication sold or distributed through the mails or otherwise, to paid subscribers during the twelve months preceding the date shown above is ————————. (This information is required from daily publications only.)

COLIN C. CAMPBELL (Signed)

Sworn to and subscribed before me this 2nd day of October, 1950.
[SEAL]

JEAN GRANT REAMES (Signed)
(My commission expires October 16, 1952.)